AquaFarm: simulation and decision support for aquaculture facility design and management planning

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Abstract

Development and application of a software product for aquaculture facility design and management planning are described (AquaFarm, Oregon State University©). AquaFarm provides: (1) simulation of physical, chemical, and biological unit processes; (2) simulation of facility and fish culture management; (3) compilation of facility resource and enterprise budgets; and (4) a graphical user interface and data management capabilities. These analytical tools are combined into an interactive, decision support system for the simulation, analysis, and evaluation of alternative design and management strategies. The quantitative methods and models used in AquaFarm are primarily adapted from the aquaculture science and engineering literature and mechanistic in nature. In addition, new methods have been developed and empirically based simplifications implemented as required to construct a comprehensive, practically oriented, system level, aquaculture simulator. In the use of AquaFarm, aquaculture production facilities can be of any design and management intensity, for purposes of broodfish maturation, egg incubation, and/or growout of finfish or crustaceans in cage, single pass, serial reuse, water recirculation, or solar-algae pond systems. The user has total control over all facility and management specifications, including site climate and water supplies, components and configurations of fish culture systems, fish and facility management strategies, unit costs of budget items, and production species and objectives (target fish weights/states and numbers at given future dates). In addition, parameters of unit process models are accessible to the user, including species-specific parameters of fish performance models. Based on these given specifications, aquaculture
facilities are simulated, resource requirements and enterprise budgets compiled, and operation and management schedules determined so that fish production objectives are achieved. When facility requirements or production objectives are found to be operationally or economically unacceptable, desired results are obtained through iterative design refinement. Facility performance is reported to the user as management schedules, summary reports, enterprise budgets, and tabular and graphical compilations of time-series data for unit process, fish, and water quality variables. Application of AquaFarm to various types of aquaculture systems is demonstrated. AquaFarm is applicable to a range of aquaculture interests, including education, development, and production. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Aquaculture; Decision support system; Computer; Design; Modeling; Simulation; Software

1. Introduction

Aquaculture facility design and management planning require expertise in a variety of disciplines and an ability to perform computationally intensive analyses. First, following specification of the physical, chemical, biological, and management processes used to represent a given facility, quantitative procedures are required to model these processes, project future facility performance, and determine facility operational constraints and capacities. Second, management of large datasets is often necessary, including facility and management specifications, projected facility performance and management schedules, and resource and economic budgets. Finally, design procedures require many calculations, especially when: (1) multiple fish lots and fish rearing units are considered; (2) simulation procedures are used to generate facility performance and management schedules; (3) alternative design and management strategies are compared; (4) designs are adjusted and optimized through a series of iterative facility performance tests; and (5) production economics are compared over a range of production scales. Such analyses can be used to optimize production output with respect to required management intensity and resource consumption (or costs) and to explore tradeoffs between fish biomass densities maintained and fish production throughput achieved (residence time of fish in a facility).

To address these challenges, computer software tools for facility design and management planning can embody expertise in aquaculture science and engineering and serve as mechanisms of technology transfer to education, development, and production. In addition, computer tools can assume the burden of data management and calculation processing and thereby reduce the workload of design and planning analyses. A current listing and description of software for aquaculture siting, planning, design, and management is available on the Internet (Ernst, 1998). Much of this software falls under the general heading of decision support systems (Sprague and Watson, 1986; Hopgood, 1991), in which quantitative methods and models, rule-based planning and diagnostic procedures (expert systems), and databases are packaged into interactive software applications. The application of decision support systems to aquaculture is relatively recent and has been preceded
by the development of simulation models for research purposes. Foretelling these
trends, decision support systems have been developed for agriculture for purposes
of market analysis, selection of crop cultivars, crop production, disease diagnosis,
and pesticide application.

The purpose of this paper is to provide an overview of the development and
application of AquaFarm (Ver. 1.0, Microsoft Windows®, Oregon State University©). AquaFarm is a simulation and decision support software product for the
design and management planning of finfish and crustacean aquaculture facilities
(Ernst, 2000b). Major topics in this discussion are: (1) the division of aquaculture
production systems into functional components and associated models, including
unit processes, management procedures, and resource accounting; and (2) the
flexible reintegration of these components into system-level simulation models and
design procedures that are adaptable to various aquaculture system types and
production objectives. To provide this overview at a reasonable length, methods
and models of physical, chemical, and biological unit processes used in AquaFarm
are presented as abbreviated summaries in an appendix to this paper. The appendix
is organized according to domain experts and unit processes. Example applications
of AquaFarm to typical design and planning problems are provided but rigorous
case studies are beyond the scope of this paper. Completed and ongoing calibration
and validation procedures for AquaFarm are discussed.

2. AquaFarm development

The aquaculture science and engineering literature was applicable to the develop-
ment of AquaFarm through three major avenues. First, studies concerned with
aquaculture unit processes and system performance provided models and modeling
overviews for a wide range of physical, chemical, and biological unit processes and
system types (Chen and Orlob, 1975; Muir, 1982; Bernard, 1983; Allen et al., 1984;
James, 1984; Svirezhev et al., 1984; Cuenco et al., 1985a,b,c; Fritz, 1985;
Tchobanoglous and Schroeder, 1985; Cuenco, 1989; Piedrahita, 1990; Brune and
Tomasso, 1991; Colt and Orwicz, 1991b; McLean et al., 1991; Piedrahita, 1991;
Weatherly et al., 1993; Timmons and Losordo, 1994; Wood et al., 1996; Piedrahita
et al., 1997). Additional methods and models were newly developed for AquaFarm,
including empirically based simplifications, as required to achieve comprehensive
coverage of aquaculture system modeling while avoiding excessive levels of com-
plexity and input data requirements. AquaFarm is primarily based on mechanistic
principles, with empirical components added as necessary to support practically
oriented design and management analyses for a wide range of users.

A second area of useful literature were studies that provided methods and results
of aquaculture production trials that could be used for the calibration and
validation of unit process and fish performance models. These studies consisted
mainly of technical papers, plus a few published databases, and are cited as they are
used in this paper. Finally, papers reporting software development for end users
have introduced computerized analysis tools and decision support systems to
aquaculture educators, developers, and producers (Bourke et al., 1993; Lannan, 1993; Nath, 1996; Leung and El-Gayar, 1997; Piedrahita et al., 1997; Schulstad, 1997; Wilton et al., 1997; Stagnitti and Austin, 1998). These reported software applications range widely in their internal mechanisms and intended purpose. The software POND (Nath et al., 2000) is most similar to AquaFarm and some program modules have been jointly developed.

In the development of AquaFarm, it was desired to maintain a practical balance between the responsibilities required from users and the analytical capacity provided by AquaFarm. These objectives are somewhat opposed, and a considerable level of user responsibility was found necessary to achieve desired levels of analysis. User responsibilities required in the use of AquaFarm consist of facility specifications, model parameters, and decisions regarding alternative facility designs and management strategies. Facility specifications include items such as facility location (for generated climates) or climatic regimes (for file-based climates), source water variables, components and configurations of water transport, water treatment, and fish culture systems, management strategies, and production objectives. While approximate environmental conditions, typical facility configurations, and typical management strategies can be provided by AquaFarm, it is not possible to avoid user responsibility for these site-specific variables. In contrast, model parameters for passive unit processes (e.g. passive heat and gas transfer and biological processes) are ideally independent of site-specific conditions, given the use of sufficiently developed models. Validated, default values are provided for all parameters. However, due to the necessity of simplifying assumptions and aggregated processes in aquacultural modeling, model parameters may be dependent on site-specific conditions to some degree (Svirezhev et al., 1984). Thus, model parameters for passive unit processes have been made user accessible for any necessary adjustment. Finally, while the purpose of AquaFarm is to support design and management decisions, these decisions must still be made by the user. As a result, some level of user responsibility cannot be avoided regarding the underlying processes impacting system performance and implications of alternative decisions on facility performance and economics. Possible methods to alleviate user responsibilities are discussed in the conclusion to this paper.

AquaFarm was developed to support a wide range of extensive and intensive, fishery-supplementation and food-fish aquaculture facilities, and a wide range of user perspectives (e.g. educators, developers, and producers), within a single software application. Differing analytical needs of these various systems and users have been addressed through an adaptable user interface. An alternative strategy would have been the development of separate software applications for each major type of aquaculture, type of user, and user knowledge level. The development approach used was chosen to avoid requirements for redundant programming, given the large overlap in analytical methods, simulation processing, graphical interface, and data management requirements over the range of aquaculture system types and analytical perspectives. In addition, some aquaculture system types are not easily categorized, for example intensive tank-based recirculation systems characterized by significant levels of phytoplankton and semi-intensive pond-based systems using recirculation systems for phytoplankton management.
AquaFarm is a stand-alone computer application, programmed in Borland C++ and requiring a PC-based Microsoft Windows® operating environment. The C++ computer language was chosen for its popularity, portability, availability of software developer tools, compatibility with the chosen graphical user interface (Microsoft Windows®), and support of object oriented programming (OOP; Budd 1991; Nath et al., 2000). According to OOP methods, all components of AquaFarm are represented as program ‘objects’. These objects are used to represent abstract entities (e.g. dialog box templates) and real world entities (e.g. fish rearing units) and are organized into hierarchical structures. Each object contains data, local and inherited methods, and mechanisms to communicate with other objects as needed. The modular, structured program architecture supported by OOP is particularly suited to the development of complex system models such as AquaFarm.

3. AquaFarm design procedure

AquaFarm supports interactive design procedures, utilizing progressive levels of analysis complexity, simulation based analyses, and iterative design refinement (James, 1984e). These procedures are used to develop design and management specifications, until production objectives are achieved or are determined to be biologically or practically infeasible. This decision making process is user directed and can be used to design new systems or determine production capacities for existing systems. The analysis resolution level (Table 1) is set so that the complexity of design analyses is matched to levels appropriate for the type of aquaculture system and stage of the design procedure. This is accomplished by user control over the particular variables and processes considered in a given simulation. For example, dissolved oxygen can be ignored or modeled as a function of one or more sources and sinks, including water flow, passive and active gas transfer, fish consumption, and bacterial and phytoplankton processes. Major steps of a typical design procedure are listed below and flow charted in Fig. 1. A summary of input and output data considered by AquaFarm is provided in Table 2.

1. Resolution. An analysis resolution level is selected that is compatible with the type of facility and stage of the design procedure.
2. Specification. Facility environment, design, and management specifications are established, based on known and tentative information.
3. Simulation. The facility is simulated to generate facility performance summaries and operation schedules over the course of one or more production seasons.
4. Evaluation. Predicted facility performance and operation are reviewed and evaluated, using summary reports, tabular and graphical data presentation, management logs, and enterprise budgets.
5. Iteration. As necessary, facility design, management methods, and/or production objectives are adjusted so that production objectives and other desired results are achieved (go to step 1 or 2).
Table 1
Variables and processes considered by AquaFarm for analysis resolution levels (ARL) I–V

<table>
<thead>
<tr>
<th>ARL</th>
<th>Water quality and loading variables</th>
<th>Facility unit and fish lot processes</th>
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<tr>
<td>I</td>
<td>Day length (h)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Weather, water mechanics and hydrodynamics, and passive/active heat transfer.</td>
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<td></td>
<td>Temperature (°C)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Fish survival, development and growth, feeding on prepared feeds, and natural fish productivity based on fish density.</td>
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<td>Salinity (ppt)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Water flow rate (m³ day&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Hydraulic loading (m³ m&lt;sup&gt;-2&lt;/sup&gt; day&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>Hydraulic retention (d&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Water velocity (cm s&lt;sup&gt;-1&lt;/sup&gt; and fish body lengths s&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Fish biomass density (kg m&lt;sup&gt;-3&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Fish biomass loading (kg m&lt;sup&gt;-3&lt;/sup&gt; day&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Feed loading (kg day&lt;sup&gt;-1&lt;/sup&gt; per m³ day&lt;sup&gt;-1&lt;/sup&gt;–kg m&lt;sup&gt;-3&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>II</td>
<td>Dissolved oxygen (DO, mg O&lt;sub&gt;2&lt;/sub&gt; l&lt;sup&gt;-1&lt;/sup&gt; and% saturation)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Oxygen mass balances based on water flow, passive and active transfer, and fish metabolism.</td>
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<td>Cumulative oxygen consumption (COC, mg O&lt;sub&gt;2&lt;/sub&gt; l&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>III</td>
<td>pH (NBS)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Mass balances for listed compounds, including acid-base chemistry, gas transfer, solids settling, soil processes, filtration of solids and compounds, compound addition, bacterial processes, and fish metabolite excretion</td>
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<td>Total alkalinity (mg CaCO&lt;sub&gt;3&lt;/sub&gt; l&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;f&lt;/sup&gt;</td>
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<td>Hardness (mg CaCO&lt;sub&gt;3&lt;/sub&gt; L&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;f&lt;/sup&gt;</td>
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<td>Dissolved nitrogen (DN, mg N l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Total gas pressure (% saturation and mm Hg)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Carbon dioxide (DC, mg CO&lt;sub&gt;2&lt;/sub&gt; 1&lt;sup&gt;-1&lt;/sup&gt; and% sat.)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Dissolved inorganic carbon (DIC, mg C L&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Total ammonia nitrogen (TAN, mg N l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Unionized ammonia (mg NH&lt;sub&gt;3&lt;/sub&gt;-N l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Nitrite (mg NO&lt;sub&gt;2&lt;/sub&gt;-N L&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Nitrate (mg NO&lt;sub&gt;3&lt;/sub&gt;-N L&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Dissolved inorganic nitrogen (DIN, mg N l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Dissolved inorganic phosphorous (DIP, mg P l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Generic fish treatment chemical (mg l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Generic water treatment chemical (mg l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Particulate inorganic and organic solids (mg l&lt;sup&gt;-1&lt;/sup&gt;, dw)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td></td>
<td>Settled inorganic and organic solids (g m&lt;sup&gt;-2&lt;/sup&gt;, dw)</td>
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<td>IV</td>
<td>Phytoplankton density (g C m&lt;sup&gt;-3&lt;/sup&gt; and mg chl-a m&lt;sup&gt;-3&lt;/sup&gt;)</td>
<td>Phytoplankton processes included in mass balances and natural fish productivity</td>
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<td>Secchi disk visibility depth (cm)</td>
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<tr>
<td>V</td>
<td>Total borate (mg B l&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>Mass balances for listed compounds</td>
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<td>Total silicate (mg Si l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>Total sulfate (mg S l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td></td>
<td>Total sulfide (mg S l&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<sup>a</sup> Variables and processes considered at each level include those in lower levels. Processes at each level can be individually selected.

<sup>b</sup> Water quality and loading variables to which fish performance can respond.

<sup>c</sup> Compounds participating in acid-base and precipitation-dissolution chemistry.

<sup>d</sup> Hydraulic loading is based on water surface area and flow rate.

<sup>e</sup> Fish and feed loading are based on water flow rate.
Fig. 1. Flowchart of the decision support procedure used by AquaFarm for aquaculture facility design and management planning, including progressive analysis levels and iterative procedures of facility and management specification, simulation, and evaluation.

In conjunction with progressive analysis resolution, a design procedure can be staged by the level of scope and detail used in specifying physical components and management strategies of a given facility. For example, design analyses can start with fish performance, using simplified facilities and a minimum of water quality variables and unit processes. When satisfactory results are achieved at simpler levels, increased levels of complexity for modeling facility performance and management strategies are used. By this approach, the feasibility of rearing a given species and biomass of fish under expected environmental conditions is determined before the specific culture system, resource, and economic requirements necessary to provide this culture environment are developed. Major stages of a typical design procedure are listed below, but this progression is completely user controlled.

1. Production trajectory. Fish development, growth, and feeding schedules for broodfish maturation, egg incubation, and/or fish growout are determined based
on initial and target fish states. Environmental quality concerns are limited to water temperature and day length, and unit processes are limited to water flow and heat transfer.

2. Production scale. Required water area and volume requirements for fish rearing units are determined, based on initial and target fish numbers, management methods, and biomass density criteria. Natural fish productivity, if considered, is a function of fish density only.

3. Biomass support. Based on fish feed and metabolic loading, facility water transport and treatment systems are constructed to provide fish rearing units with required water flow rates and water quality. The particular variables and unit processes considered depend on the type of facility. Natural fish productivity, if considered, is a function of fish density and primary productivity.

4. Management schedules. Fish and facility management methods and schedules are finalized, including operation of culture systems, fish lot handling, and fish number, weight, and feeding schedules.

5. Resource budgets. Resource and enterprise budgets are generated and reviewed.

Table 2
Summary of input specification and output performance data considered by AquaFarm

Input specification data
Possible adjustment of parameters for passive physical, chemical, and biological unit processes and fish performance models
Facility location (or climate data files), optional facility housing and controlled climate, and water quality and capacity of source water(s)
Configuration of facility units for facility water transport, water treatment, and fish culture systems
Specifications of individual facility units, including dimensions, elevations and hydraulics, soil and materials, housing, and water transport and treatment processes
Fish species, fish and facility management strategies, and production objectives (target fish weights/states and numbers at given future dates)
Unit costs for budget items and additional budget items not generated by AquaFarm

Output performance data
Fish number and development schedules for broodfish maturation and egg incubation
Fish number, weight, and feed application schedules for fish growout, including optional consideration of fish weight distributions within a fish lot
Fish rearing unit usage and fish lot handling schedules
Tabular and graphical compilations of time-series data for fish performance variables, reported on a fish population and individual fish lot basis, including fish numbers and state, bioenergetic and feeding variables, and biomass loading and water quality variables
Tabular and graphical compilations of time-series data for facility performance variables, reported on a facility and individual facility unit basis, including climate, water quality, fish and feed loading, water flow rates and budgets, compound budgets, process rates, resource use, waste production, and water discharge
Fish production reports, resource use summaries, and enterprise budgets
4. AquaFarm architecture and components

AquaFarm consists of six major components: (1) graphical user interface; (2) data manager; (3) simulation manager; (4) domain experts; (5) facility components; and (6) facility managers (Fig. 2). The first three of these are specific to AquaFarm while the last three represent real-world entities. Domain experts provide expertise in various knowledge domains and include an aquatic chemist, aquacultural engineer, aquatic biologist, fish biologist, and enterprise accountant. Facility components represent the physical facility and include facility units, resource units, fish stocks, fish populations, and fish lots. Facility managers are responsible for facility management tasks and production scheduling and include a physical plant manager and fish culture manager.
4.1. User interface and data management

The user interface is typical of window based software, providing a hierarchical menu system and selectable viewing windows that support general-to-specific interface navigation. Types of windows include tool bars, facility maps, specification sheets, output tables and graphs, management schedules, budget spreadsheets, and user help screens. An example of the interface is shown in Fig. 3 (see recirculation systems under AquaFarm application for additional explanation). According to the type of facility under design and analysis resolution level in use, user access to windows, controls, and data fields is limited to relevant items. Data files are used to store and retrieve user projects, with specification and review mechanisms for data files provided within AquaFarm. Output data can be exported in delimited format for use in computer spreadsheets.

Fig. 3. Example window of AquaFarm’s user interface, showing the main menu and a facility map. The example shown is a water recirculation facility, consisting of fish rearing units supplied by a single recirculation loop with a water makeup supply and water/solids discharge (see Table 3 for key to facility unit names).
4.2. Domain experts

Domain experts provide expertise in aquaculture science and engineering in the form of quantitative methods and models. These methods consist of property, equilibrium, and rate calculations of physical, chemical, and biological unit processes and their rules of application. These methods are used to calculate terms in facility-unit and fish-lot state equations and to support management analyses. The documentation required to fully describe these methods is not possible within the size constraints of this paper. Methods of the aquatic chemist, aquacultural engineer, aquatic biologist, and fish biologist are summarized in the appendix, and the enterprise accountant is described below.

4.2.1. Enterprise accountant

The enterprise accountant is responsible for compiling enterprise budgets, which are used to quantify net profit or loss over specified production periods (Meade, 1989; Engle et al., 1997). Enterprise budgets are particularly appropriate for comparing alternative facility designs, in which partial budgets are utilized that focus on cost and revenue items significantly influenced by proposed changes. Additional financial statements (e.g. cash flow and net worth), economic feasibility analyses (e.g. net present value and internal rate of return), and market analyses are required for comprehensive economic analyses (Shang, 1981; Allen et al., 1984; Meade, 1989) but are not supported by AquaFarm.

Cost items (e.g. fish feed) and revenue items (e.g. produced fish) can be specified and budgets can be summarized according to various production bases, time periods, and cost types. Item and budget bases include per unit production area, per unit fish production, and per total facility. Item and budget periods include daily, annual, and user specified periods. Cost types include fixed and variable costs, as determined by their independence or dependence on production output, respectively. Fixed costs include items such as management, maintenance, insurance, taxes, interest on owned capital (opportunity costs), interest on borrowed capital, and depreciation for durable assets with finite lifetimes. Variable costs include items such as seasonal labor, energy and materials, equipment repair, and interest on operational capital.

Enterprise budgets are built by combining simulation-generated and user-specified cost and revenue items. Simulation generated items are those directly associated with aquaculture production and therefore predictable by AquaFarm, e.g. facility units, energy and material consumption, and produced fish and wastes. AquaFarm determines total quantities for these items (numbers of units), but the user is responsible for unit costs and other specifications (e.g. interest rates, useful lives, and salvage values). User specified items include additional cost and revenue items outside the scope of AquaFarm, e.g. supplies, equipment, facility infrastructure, and labor. For user specified items that are scalable, the use of unitized cost bases (i.e. per unit production area or production output) alleviates the need to re-specify item quantities when working through multiple design scenarios. The budget is shown in spreadsheet format for the selected budget basis and period,
with cost and revenue items totaled and net profit or loss calculated. Net profit values can also be used as net return values to cost items that are not included in the budget, e.g. net return to land, labor, and/or management.

4.3. Facility site, facility units, and resource units

An aquaculture facility is represented by a facility site, facility units, and resource units. A facility site consists of a given location (latitude, longitude, and altitude), ambient or controlled climate, and configuration of facility units. Facility units consist of water transport units, water treatment units, and fish rearing units (Table 3). Resource units supply energy and material resources to facility units, maintain combined peak and mean usage rates for sizing of resource supplies, and compile total resource quantities for use in enterprise budgets (Table 4). A facility configuration is completely user specified and can consist of any combination of facility unit types linked into serial and parallel arrays. A facility is built by selecting (from menu), positioning, and connecting facility units on the facility map. Each type of facility unit is provided with characteristic processes at construction, to which additional processes are added as needed. Facility units are shown to scale, in plan view, color coded by type, and labeled by name. To visualize the progress of simulations, date and time are shown, colors used for water flow routes denote presence of water flow, and fish icons over rearing units denote presence of fish as they are stocked, removed, and moved within the facility.

4.3.1. Facility-unit specifications

Facility unit specifications include housing, dimensions and materials, and actively managed processes of water transport, water treatment, and fish production. The purpose of these specifications is to support facility unit modeling. Individual unit processes and associated specifications can be ignored or included, depending on user design objectives and analysis resolution level. Default facility unit specifications are provided during facility construction, but these variables are highly specific to a particular design project and therefore accessible. Managed (active) processes of water transport, water treatment, and fish production are operated according to the specifications of individual facility units, in addition to management criteria and protocols assigned to facility managers. Water quality is specified for water sources, including temperature regimes, gas saturation levels, optional carbon dioxide and calcium carbonate equilibria conditions, and constant values for the remaining variables. For soil lined facility units, soils are indirectly specified through given water seepage and compound uptake and release rates.

Facility units can be housed in greenhouses or buildings, with controlled air temperature, relative humidity, day length, and light intensity (solar shading and/or artificial lighting). Facility units can be any shape and dimensions, constructed from soil or materials, and any elevation relative to local soil grade. Top, side, and/or bottom walls can be constructed from a variety of structural, insulating, water impermeable, and cage mesh materials. Hydraulic specifications include facility unit elevations and slope, water flow type (basin, gravity, cascade, or pressurized), water
Table 3
Facility unit types and primary processes*

<table>
<thead>
<tr>
<th>Facility unit type</th>
<th>Primary processes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water transport units</strong></td>
<td></td>
</tr>
<tr>
<td>Source (SRC)</td>
<td>Facility influent flow capacity and water quality</td>
</tr>
<tr>
<td>Discharge (DCH)</td>
<td>Facility effluent cumulative water and compound discharge</td>
</tr>
<tr>
<td>Pump (PMP)</td>
<td>Water pump performance and power/air consumption for centrifugal and airlift pumps</td>
</tr>
<tr>
<td>Pipe (PIP)</td>
<td>Pressurized and gravity water flow mechanics</td>
</tr>
<tr>
<td>Channel (CHN)</td>
<td>Gravity water flow mechanics</td>
</tr>
<tr>
<td>Blender/splitter (ABS)</td>
<td>Flow stream blending for temperature and salinity adjustment and flow stream division for specialized management (e.g. recirculation) (active)</td>
</tr>
<tr>
<td>Flow node (PBS)</td>
<td>Flow stream blending, division, and redirection (passive)</td>
</tr>
<tr>
<td><strong>Water treatment units</strong></td>
<td></td>
</tr>
<tr>
<td>Water basin/tank (BSN/TNK)</td>
<td>Water retention for head and sump tanks and a variety of water treatment processes</td>
</tr>
<tr>
<td>Gas exchanger (GAS)</td>
<td>Water aeration, degassing, and oxygenation in air-contact units and pure oxygen absorbers, including packed/spray columns, water surface aerators, submerged venturis and diffusers, and oxygenators</td>
</tr>
<tr>
<td>Heat exchanger (HCX)</td>
<td>Water heating and chilling using inline and in-tank, elements and exchangers</td>
</tr>
<tr>
<td>Mechanical filter (FLT)</td>
<td>Filtration of particulate solids, including granular media filters, porous media filters, micro screens, particle separators (hydroclones, swirl separators), and foam fractionators</td>
</tr>
<tr>
<td>Chemical filter (CFL)</td>
<td>Filtration of ammonium by ion-exchange (clinoptilolite) and chlorine by adsorption (granular activated carbon)</td>
</tr>
<tr>
<td>Biological filter (BIO)</td>
<td>Bacterial conversion of nitrogen compounds by fixed-film nitrification or denitrification biofilters (trickling, RBC, expandable granular media, and fluidized bed). Wetland and hydroponic units for nutrient uptake (DIN and DIP) and retention of particulate solids.</td>
</tr>
<tr>
<td>Compound supplier (CHM)</td>
<td>Addition of water treatment compounds for water conditioning, nutrient supply, disinfection, and fish treatment</td>
</tr>
<tr>
<td><strong>Fish rearing units</strong></td>
<td></td>
</tr>
<tr>
<td>Broodfish holding (BRU)</td>
<td>Broodfish maturation: biomass, feed, and metabolic loading</td>
</tr>
<tr>
<td>Egg incubator (ERU)</td>
<td>Egg incubation: biomass and metabolic loading</td>
</tr>
<tr>
<td>Growout rearing (FRY-, FNG-, J/A-GRU)</td>
<td>Fish growout: biomass, feed, and metabolic loading (default types: fry, fingerling, and juvenile/adult)</td>
</tr>
</tbody>
</table>

* Names in parentheses are abbreviations for facility mapping. Processes in addition to primary processes can be considered depending on facility unit type (e.g. inclusion of gas exchangers and compound suppliers in fish rearing units or hydraulic solids removal in a water splitter)
4.3.2. Facility-unit state variables

In addition to facility unit specifications, which are fixed variables for a given simulation, facility units are defined by dynamic state variables that vary over the course of a simulation (Table 1). Most of these variables correspond to those typically used. Fish and feed loading variables and cumulative oxygen consumption (Colt and Orwicz, 1991b) are included to support analyses that use these variables as management criteria and for reporting purposes. Alkalinity and pH relationships include consideration of dissolved inorganic carbon (carbon dioxide and carbon-

<table>
<thead>
<tr>
<th>Resource type</th>
<th>Resource description (given units reported per day, per year, or per production season)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility units</td>
<td>Total numbers of each type of facility unit and quantities of materials used (m² or m³): metal, wood, concrete, fiberglass, PVC, PE, ABS, acrylic, glass, shade tarp, and insulation</td>
</tr>
<tr>
<td>Supply water</td>
<td>Source water consumption (m³)</td>
</tr>
<tr>
<td>Discharge water</td>
<td>Cumulative discharge water (m³) and quantities of solids, DIN, DIP, BOD, and COD (kg)</td>
</tr>
<tr>
<td>Waste materials</td>
<td>Waste sludge (kg, dw), spent filter media (m³), and dead fish (kg)</td>
</tr>
<tr>
<td>Energy</td>
<td>Energy consumed by facility lighting, water pumps, gas and heat exchangers, UV sterilizers, etc., expressed as electrical power (kWhr) or energy equivalent of liquid fuels (L; gasoline, methanol, and diesel) or gas fuels (m³; natural gas, propane, and methane)</td>
</tr>
<tr>
<td>Compressed air</td>
<td>Compressed air for air-lift pumps, column aerators (optional), air diffusers, and foam fractionators (m³; equivalent energy as kWhr for air compression and delivery)</td>
</tr>
<tr>
<td>Water treatment</td>
<td>Compounds added to water for water treatment (kg): (1) Inorganic and organic fertilizers (user specified composition), (2) pH and alkalinity adjustment compounds (carbon dioxide, nitric, sulfuric, and phosphoric acid, sodium hydroxide, sodium bicarbonate and carbonate, agricultural limestone, and hydrated and burnt lime), and (3) pure oxygen, sea salt, and various user-defined fish/egg treatment, water conditioning, and water disinfection compounds</td>
</tr>
<tr>
<td>Filter media</td>
<td>Filter media for mechanical, chemical, and biological filters (m³): sand, expanded plastic, plastic beads, gravel/rock, fabric, clinoptilolite, granular activated carbon, and hydroponic and wetland materials. Quantities include original and replacement media, the latter based on the allowed number of regeneration cycles</td>
</tr>
<tr>
<td>Fish feed</td>
<td>Prepared fish feeds (kg): larval, flake, mash, pellet sizes 0.5 to 10.0 mm, and broodfish feeds</td>
</tr>
<tr>
<td>Stocked and produced fish</td>
<td>Broodfish, eggs, and growout fish (number, kg) input and output by the facility</td>
</tr>
<tr>
<td>Labor</td>
<td>To assist specification of required labor, the enterprise budget provides: (1) per unit production area and per unit fish production cost bases; (2) total time of fish culture (days); and (3) numbers of management tasks completed for process rate adjustments and fish feeding and handling events</td>
</tr>
</tbody>
</table>

* Additional facility infrastructure, equipment, supplies, and labor resources are the responsibility of the user and are specified at the facility enterprise budget.
ates) and additional constituents of alkalinity (conjugate bases of dissociated acids).
Constituents of dissolved inorganic nitrogen include ammonia, nitrite, and nitrate, and dissolved nitrogen gas can be considered. Dissolved inorganic phosphorus is considered equivalent to soluble reactive phosphorus (orthophosphate) and consists of ionization products of orthophosphoric acid (Boyd, 1990). For simplicity, other dissolved forms of phosphorus are not considered and inorganic phosphorus applied as fertilizer is assumed to hydrolyze to the ortho form based on given fertilizer solubilities. Nitrogen and phosphorus are variable constituents of organic particulate solids, released in dissolved form when these solids are oxidized. Fish and water treatment chemicals are user-defined compounds that may be used for a variety of purposes, such as control of fish pathogens, water disinfectants and compounds present in source waters (e.g. ozone and chlorine), and water conditioning (e.g. dechlorination). Borate, silicate, and sulfate compounds can have minor impacts on acid-base chemistry, especially for seawater systems, but can normally be ignored.

Particulate solids are comprised of suspended and settleable, inorganic and organic solids (expressed in terms of dry weight, dw; live phytoplankton not included). Suspended inorganic solids (clay turbidity) are considered in order to account for their impact on water clarity (expressed as Secchi disk visibility), which is a function of total particulate solid and phytoplankton concentrations. Settleable inorganic and organic solids originate from various sources, e.g. in/organic fertilizers, dead phytoplankton, uneaten feed, and fish fecal material. Settling rates and carbon, nitrogen, and phosphorus contents of these solids depend on their sources. Settled solids originate from combined inorganic and organic settleable solids, and their composition varies in response to their sources.

4.3.3. Facility-unit processes

Physical, chemical, and biological mass-transfer processes and associated compound sources and sinks that can occur in facility units are listed in Table 5. In addition, water flow mechanics and heat transfer are represented by energy transfer processes. Methods used to model these mass and energy transfer processes (unit processes) are summarized in Appendix A. Unit processes can be individually selected for consideration, depending on user design objectives and analysis resolution level. Unit processes can be passive, active, or both passive and active, and are simulated accordingly. Examples of passive processes are water surface heat and gas transfer, bacterial processes, and primary productivity. Passive processes may be uncontrolled or indirectly controlled, e.g. primary productivity can be indirectly managed through the control of nutrient levels. Actively managed processes are directly controlled to maintain water quantity and quality variables at desired levels. Examples of active processes are water flow rate, heating, aeration, solids filtration, and compound addition. Air-water gas transfer of a fish pond is an example of a combined passive-active process, in which aeration is used in response to low oxygen levels but passive air-water gas transfer is also significant. Generally, in the context of this discussion, passive processes are defined by model parameters and active processes are defined by facility specifications.
Table 5
Presence of sources (added: +) and sinks (removed: –) of the listed compounds for the physical, chemical, and biological mass transfer processes occurring in facility units

<table>
<thead>
<tr>
<th>Compound</th>
<th>Facility unit processes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FLO</td>
</tr>
<tr>
<td>DO</td>
<td>+/–</td>
</tr>
<tr>
<td>DN</td>
<td>+/–</td>
</tr>
<tr>
<td>Salinity</td>
<td>+/–</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>+/–</td>
</tr>
<tr>
<td>Hardness</td>
<td>+/–</td>
</tr>
<tr>
<td>DIC</td>
<td>+/–</td>
</tr>
<tr>
<td>TAN</td>
<td>+/–</td>
</tr>
<tr>
<td>Nitrite</td>
<td>+/–</td>
</tr>
<tr>
<td>Nitrate</td>
<td>+/–</td>
</tr>
<tr>
<td>Particulate solids</td>
<td>+/–</td>
</tr>
<tr>
<td>Settled solids</td>
<td>0</td>
</tr>
<tr>
<td>Phytoplankton</td>
<td>+/–</td>
</tr>
<tr>
<td>Treatment chem.</td>
<td>+/–</td>
</tr>
<tr>
<td>Sulfide</td>
<td>+/–</td>
</tr>
<tr>
<td>B, S, S (sulfate)</td>
<td>+/–</td>
</tr>
</tbody>
</table>

*See Table 1 for definitions of compound names. Use of '0' denotes absence of mass transfer or lack of consideration by AquaFarm.

b FLO, influent (+) and effluent flow (–) (also water seepage and precipitation, see text); DIF, passive and active, air-water gas diffusion (DIC as DC and TAN as unionized ammonia); CMP, compound addition to water; FLT, mechanical, chemical, and hydroponic/wetland biological filters (other biological filters under NIT and DNT); CHM, calcium carbonate dissolution (+) and precipitation (–) and decay of treatment chemicals; SOL, soil release (+) and uptake (–); SST, solids settling (inorganic particulate solids; no settling of live phytoplankton); OXD, heterotrophic bacterial processes; NIT, nitrification bacterial processes (passive and biological filters); DNT, denitrification bacterial processes (passive and biological filters); NPP, phytoplankton processes for NPP > 0 (if NPP < 0, reverse signs). Alkalinity is removed for TAN uptake and added for nitrate and DN uptake. DN use depends on presence of blue-green algae and DIN levels. Dead phytoplankton become particulate organic solids; FSM, fish metabolic processes, compound excretion (+) and consumption (–); FSC, fish consumption of endogenous food resources.
In addition to compounds, the water volume contained by a facility unit is subject to mass transfer, including influent and effluent flow, seepage infiltration and loss, precipitation and runoff, and evaporation. Compound transfer via water transfer are based on the assumptions that seepage water constituents are comparable to the bulk water volume, precipitation water is pure other than dissolved gases, and evaporation water has no constituents. Settled solids accumulate as a function of contributing particulate solids and settling rates, their lack of disturbance (scouring), and incomplete bacterial oxidation. The accumulation of settled solids can remove significant quantities of nutrients and oxygen demand and provide local anaerobic conditions that support denitrification. Settled solids can be removed by periodic manual procedures (e.g. rearing unit vacuuming and filter cleaning) or continuous hydraulic procedures (e.g. dual-drain effluent configurations).

Facility unit differential equations are based on completely mixed hydraulics (James, 1984a; Tchobanoglous and Schroeder, 1985). While plug-flow hydraulics characterize certain types of facility units, e.g. raceway fish rearing units, the necessity to consider plug-flow hydraulics with respect to overall simulation accuracy is currently being assessed. When water stratification is considered, a facility unit is modeled as two horizontal water layers of equal depth, and process rates and state variables associated with each layer are maintained separately. Each of these layers is completely mixed internally, and layers inter-mix at a rate dependent on environmental conditions. Possible stratified processes include physical processes (e.g. surface heat and gas transfer), chemical processes (e.g. pond soils), and biological processes (e.g. primary productivity and settled solid oxidation). Possible stratified water quality variables include temperature, dissolved gases, pH and alkalinity, nitrogen and phosphorous compounds, and organic particulate solids. For simplification, phytoplankton are assumed to maintain a homogenous distribution over the water column.

4.3.4. Water transport units

Water transport units are used to contain, blend, divide, and control water flow streams (Table 3). Water transport units are installed as necessary to adequately represent water transport systems and determine flow rate capacity limits and pump power requirements. To simplify facility construction, pipe fittings (e.g. elbows, tees, and valves) and short lengths of pipes and channels can be ignored. For clarity in facility mapping, however, water flow nodes can be used to represent all points of blending, division, and redirection of water flow streams by pipe fittings and channel junctions. Any facility unit can have multiple influent and effluent flow streams. Minor head losses of pipefittings are calculated as a proportion of the major head losses of associated pipe lengths. Flow control devices for pipes and channels are assumed to exist, but they are not explicitly defined. Specialized water blenders and splitters are used for designated purposes, such as water flow blending for temperature and salinity adjustment and water flow division to achieve desired water recirculation rates.
4.3.5. Water treatment units

Water treatment units are used to add, remove, and convert water borne compounds and adjust water temperature (Table 3). Water treatment units typically specialize in a particular unit process, but processes can be combined with a single facility unit as desired. Water treatment processes are primarily defined by their given efficiencies or control levels. Specifications include set-point levels, set-point tolerances, efficiencies of energy and material transfer, minimum and maximum allowed process rates, and process control methods.

Process efficiency is the primary control variable for filtration processes that remove compounds from the water. For mechanical and chemical filters, process efficiency is specified as percent removal of the given compound per pass of water through the filter. For biological filters, process efficiency is specified as kinetic parameters of bacterial processes. For all filters, periodic requirements for media cleaning (removal of accumulated solids) or regeneration (e.g. clinoptilolite and granular activated carbon) over the course of a simulation can be accomplished manually by the facility manager or automatically by the facility unit.

Set-point level is the primary control variable for processes that add compounds to the water and for temperature adjustment, for which the units used to express set-point levels are those of the controlled variable. Pond fertilization is managed with respect to set points for DIC, DIN, and/or DIP. For each process, constant rate, simple on/off, and proportional (throttled) process control methods can be used, the latter providing process rates that vary continuously or in discrete steps over their given operational ranges. Integral-derivative process control can be combined with proportional control so that the rate of change and projected future level of the controlled variable are considered in rate adjustments. Proportional and integral-derivative controls are used to minimize oscillation of the controlled variable around its set-point level (Heisler, 1984). Process control can be accomplished manually by the facility manager or automatically by the facility unit. For some conditions, for example when both heaters and chillers are present, the controlled variable can be both decreased and increased to achieve a given set point. More typically, controlled variables can only be decreased or increased, for example the addition of a compound to achieve a desired concentration. Set-point tolerances and minimum and maximum allowed process rates are normally required for realistic simulations, for example diurnal control of fish pond aerators in response to dissolved oxygen.

4.3.6. Fish rearing units

Fish rearing units can be designated for particular fish stocks (species), fish life stages (broodfish, eggs, and growout fish), and fish size stages (e.g. fry, fingerling, and juvenile/adult) (Table 3). This supports movement of fish lots within the facility based on fish size and management of multiple life stage, multi-species, and polyculture facilities. Fish rearing units can include most water treatment processes, e.g. fertilization, liming, and aeration for pond based aquaculture, and can utilize process control methods as described for water treatment units.
4.4. Fish stocks, populations, and lots

Production fish are represented at three levels of organization: fish stocks, fish populations, and fish lots. A fish stock consists of one or more fish populations, and a fish population is divided into one or more fish lots. A fish stock is a fish species or genetically distinct stock of fish, identified by common and scientific names and defined by a set of biological performance parameters. Parameter values are provided for major aquaculture species and can be added for additional aquaculture species. Fish populations provide a level of organization for the management and reporting tasks of related, cohort fish lots. Fish populations are uniquely identified by their origin fish stock, life stage (broodfish, egg, or growout), and production year. Broodfish, egg, and growout fish populations from the same fish stock are linked by life stage transfers, i.e. from broodfish spawning to egg stocking and from egg hatching to larvae/fry stocking.

Fish lots are fish management units within a fish population. Fish lots are defined by their current location (rearing unit), population size, and development state. The latter consists of accumulated temperature units (ATU) and photoperiod units (APU) for broodfish lots, accumulated temperature units for egg lots, and fish body weights for growout fish lots. At a point in time, fish lot states are maintained as mean values and fish weights within a growout fish lot can be represented as weight distributions (histograms). Variability in fish weights within a growout fish lot can be due to variability present at facility input, fish lot division and combining, and variability in fish growth rates due to competition for limited food resources. Target values for fish lot numbers and states are specified as production objectives or, in the case of broodfish and egg target states, represent biological requirements. Initial values for these variables can be user specified, result from life stage transfers, or result from fish stocking conditions that are required to achieve fish production objectives. Intermediate fish lot numbers and states are predicted by simulation. Methods used to model fish survival, development and growth, feeding, and metabolism are summarized in Appendix A, under the fish biologist domain expert.

4.5. Facility managers

The facility managers are the physical plant manager and the fish culture manager. Facility managers are assigned: (1) responsibilities and variables to be monitored; (2) criteria for evaluation of monitored variables; and (3) allowed responses to correct problems. Facility managers utilize domain experts for adjusting process rates and solving management problems. A management task can be fully, partially, or not successful, depending on the availability of required facility resources. The number of possible management responsibilities and responses increases with analysis resolution and facility complexity. Facility managers perform their tasks at a given management time step, so that the desired management intensity is emulated. Facility managers report problems and responses to management logs.
4.5.1. Physical plant manager

Active managed mass and energy transfer processes of facility units are controlled by the physical plant manager to maintain water quantity and quality variables at desired levels, including water flow, heat and gas transfer, and compound conversion, addition, and removal. Based on facility specifications, active process rates can be adjusted: (1) manually, to emulate manual tasks of the physical plant manager (e.g. manual on-demand aeration); or (2) automatically, to emulate automated process control (e.g. automated on-demand aeration). Manual management tasks are simulated at the management time step, and automated management tasks are simulated at the simulation time step. For aquaculture facilities, water flow rates are based on demands at fish rearing units, as determined by the fish culture manager. For non-aquaculture facilities, water flow rates are controlled at water sources, to give constant or varying water flow rates. Water flow rates can be constrained by source water capacities and by water flow mechanics and hydraulic loading constraints of facility units. Water management schemes include: (1) static water management with loss makeup to maintain minimum volumes; (2) water flow-through with optional serial reuse; and (3) water recirculation at specified water recirculation and makeup rates.

4.5.2. Fish culture manager—production objectives

The fish culture manager is responsible for maintaining fish environmental criteria and satisfying fish production objectives. This is accomplished through the control of water flow and treatment processes, fish feeding rates, and fish biomass management. These tasks are performed according to assigned management responsibilities, fish handling and biomass loading management strategies, and available facility resources. Fish production objectives are not achieved if they exceed fish performance capacity or required facility resources are not available.

Fish production objectives are specified as: (1) calendar dates; (2) fish population numbers; and (3) fish development states (broodfish and eggs) or weights (growout fish) at initial fish stocking and target transfer events. Fish transfer events include fish input to the facility, fish life stage transfers within the facility, and fish release/harvest from the facility. Alternatively, fish stocking specifications can be determined by AquaFarm such that target objectives are achieved. Production objectives are specified as combined quantities for fish populations and are divided into component values for fish lots. Fish lots within a fish population can be managed in a uniform manner or individually specified for temporal staging of fish production. Fish management size stages can be specified for growout lots to allow assignment of designated rearing units (e.g. fry, fingerling, and on-growing) and types of fish feed (pellet size and composition) based on fish size.

4.5.3. Fish culture manager—environmental criteria

Environmental conditions are monitored at each management time step and evaluated in relation to management criteria. Variables that can be responded to include water exchange rate and velocity, fish biomass density and loading rate, feed loading rate, cumulative oxygen consumption, dissolved oxygen saturation,
carbon dioxide saturation, and concentrations of un-ionized ammonia and particulate solids (Table 1). In addition, water temperature, day length, and/or feed availability can be controlled to achieve desired fish development and growth rates. Management criteria are based on reported biological criteria for the given fish species and allowed deviations beyond designated, optimal biological ranges. Biological criteria are provided and user accessible for major aquaculture species and may be added for additional aquaculture species. For lower analysis resolution levels and systems with known capacities, water exchange rate, fish biomass density and loading rate, and/or feed loading rate can serve as measures of metabolic loading. Biomass density management can consider critical density thresholds regarding natural fish productivity and production intensity constraints, in addition to metabolic support considerations. For fish stocking, biomass density constraints are used to allocate fish lots among rearing units.

4.5.4. Fish culture manager—fish lot handling and biomass management

Fish lot handling events include fish lot stocking, combining, division, and transfer. Fish lot handling events can occur in response to: (1) fish input to the facility; (2) high variability in fish state within a fish lot; (3) low or high fish biomass density; (4) unacceptable biomass loading or water quality conditions; and (5)
achievement of threshold fish size stages, life stage transfers, and release or harvest target fish states (Fig. 4). Fish handling and biomass management responsibilities are defined by the following options.

1. The use of rearing units is prioritized such that minimum overall fish densities are maintained and either (a) fish lots are never combined or (b) lots are combined only as required to stock all lots. Alternatively, the use of rearing units is prioritized such that maximum overall fish densities are maintained and either (c) lots are combined as required to stock all lots or (d) lots are combined whenever possible to minimize use of rearing units and maximize fish densities.

2. If a facility holds multiple fish stocks, then either (a) different stocks are maintained in separate rearing units (multi-species facilities) or (b) designated stocks are combined within rearing units (polyculture facilities).

3. Fish lots are divided at stocking events to multiple rearing units as required by fish density constraints (yes/no). During culture, fish lots are transferred to smaller rearing units if fish densities are too low (yes/no), and/or fish lots are transferred whole or divided to larger rearing units if fish density is too high (yes/no).

4. Based on specified fish biomass loading and water quality criteria, (a) rearing unit water flow rates are adjusted and/or (b) fish lots are transferred whole or divided to additional rearing units (adjustment of active process rates of fish rearing units is based directly on given set-point levels).

5. Growout fish lots are graded and divided during culture to reduce excessive variability in fish weight (yes/no) and/or remove culls (yes/no). Growout fish lots are high graded and divided at transfer events to leave low grades for further culture (yes/no) and/or remove culls (yes/no).

4.5.5. Fish culture manager—management intensity and risk

Management intensity and risk levels are established through multiple specifications, including the type of facility, fish production objectives, fish lot handling strategies, fish biomass loading relative to maximum capacities, and degree of production staging and maximization of cumulative production. Based on these specifications, management intensity can range from simple batch stocking and harvest practices to staged, continuous culture, high grade harvesting and restocking practices (Watten, 1992; Summerfelt et al., 1993). Management intensity is also defined by the size of the management time step, allowed variability in growout fish weights, minimum adjustment increments of process rates, and allowed tolerances for environmental variables to exceed optimal biological ranges. Management risk is quantified as a failure response time (FRT, hours) for fish rearing units. FRT is the predicted time between failure of biomass support processes (e.g. water flow or in-pond aeration) and occurrence of fish mortality. Management risk is controlled by establishing a minimum allowed FRT for the facility. If rearing unit FRT values fall below this minimum, then fish biomass density is reduced, using the given fish lot handling rules.
4.5.6. Fish culture manager—broodfish maturation and egg incubation

Broodfish maturation is defined by accumulated temperature and/or photoperiod units. Spawning occurs when required levels of these units are achieved, as defined by species-specific parameters maintained by the fish biologist. Water temperature and day length can be controlled to achieve desired maturation rates and spawning dates. Fish population number and spawning calculations account for female-male sex ratios, egg production per female, and fish spawning characteristics (i.e. once per year, repeat spawn, or death after spawning).

Egg development is defined by accumulated temperature units. Achievement of development stages (eyed egg, hatched larvae, and first-feeding fry) is based on temperature unit requirements of each stage, as defined by species-specific parameters maintained by the fish biologist. Egg handling can be restricted during sensitive development stages. Water temperature can be controlled to achieve desired development rates and first-feeding dates.

4.5.7. Fish culture manager—fish growout

Feeding strategies for fish growout can be based on: (1) endogenous (natural) food resources only; (2) natural foods plus supplemental prepared feeds; or (3) prepared feeds only. Natural food resources can be managed indirectly by control of fish densities and maintenance of nutrient levels for primary productivity. Prepared feeds are defined by their proximate composition and pellet size, and specific feed types can be assigned to specific fish size stages. Prepared feeds are applied as necessary to achieve target growth rates, based on initial and target fish weights and dates and considering any contributions from natural foods. For daily simulations, prepared feed is applied once per day. For diurnal simulations, feed is applied according to the specified number of feedings per day and length of the daily feeding period, which can be specific to fish size stage. In addition, the impact of feed allocation strategies and application rates on food conversion efficiency and fish growth variability due to competition for limited food resources can be considered.

5. Facility and management simulation

5.1. Simulation processing

Following the establishment of facility and management specifications, facility units and fish lots are integrated and facility managers, fish populations, and resource units are updated over a series of time steps that total the simulation period. Facility components and managers are classified as simulation objects at their highest level of hierarchical abstraction in the object oriented programming architecture. The simulation of these objects is administered by the simulation manager. The simulation manager (1) maintains a simulation time clock; (2) sends update commands to simulation objects based on their time
steps; and (3) for purposes of numerical integration, maintains arrays of state variables and finite difference terms for the differential equations of facility units and fish lots. The simulation manager processes simulation objects in a generic manner and has no need to be concerned with specific details of individual objects, e.g. differential equations used to calculate difference terms or the management protocols used by facility managers.

Manual procedures of the physical plant and fish culture managers are discontinuous, discrete events. Managers respond to update commands over a series of management time steps by reviewing their assigned responsibilities, responding as facility resources allow, and logging management problems and completed tasks to management logs. In contrast, facility units and fish lots consist of continuous processes, represented by sets of simultaneous differential equations. Facility units and fish lots are simulated by solving state equations, updating state variables, and logging state variable and process rate data over a series of simulation time steps. The state variables and equations used for facility units and fish lots depend on the analysis resolution level, fish performance methods, and passive and active unit processes under consideration. At each simulation step, domain experts are used to calculate property, equilibrium, and process rate terms used in differential equations and management tasks.

5.2. Deterministic simulation

Simulations performed by AquaFarm are deterministic, in which identical results are predicted given the same set of input parameters and variable values, and all parameters and variables are expressed as mean values. Deterministic simulations can be based on worst, best, and mean case scenarios, however, as controlled by the use of worst, best, and mean expected values for input parameters and variables. Stochastic simulations are not currently supported by AquaFarm and their potential utility to AquaFarm users is under review. Stochastic simulations require multiple simulation runs (e.g. 30–100) to generate probability distributions of predicted state variables, in which selected parameters and input variables vary stochastically within and between simulations (e.g. Griffin et al., 1981; Straskraba and Gnauck, 1985; Cuenco, 1989; Lu and Piedrahita, 1998). For aquaculture systems characterized by stochastic processes, the use of deterministic simulations represents a major analytical simplification. For example, solar-algae ponds are subject to stochastic climate variables (solar radiation, cloud cover, and wind speed) and similarly managed ponds often show high variability between ponds in primary productivity and related variables. However, the additional complexity of accomplishing and interpreting stochastic simulations is considerable and prolonged computer processing times are required. As in most aquacultural modeling studies, it is assumed that deterministic simulations are useful for facility design and short and long term management decisions, even when significant stochastic behavior exists.
5.3. Numerical integration

Facility unit and fish lot differential equations can be solved by numerical or analytical methods. Under numerical integration, differential equations are used as finite difference equations to calculate finite difference terms (unit mass or energy per time). Related simulation objects are processed as a group, as determined by the existence of shared variables and simultaneous processes. State variables and finite difference terms of related simulation objects are collected into arrays at each simulation step and solved by the simulation manager using simultaneous, fourth-order Runge–Kutta integration (RK4; Elliot, 1984). RK4 integration is a powerful numerical integration method, capable of solving complex sets of simultaneous differential equations. However, RK4 integration may require small time steps, on the order of minutes to hours, when high rates of energy or mass transfer characterized by first-order kinetics exist in facility units (e.g. high rates of water flow, active gas transfer, or fixed-film bacterial processes). In addition, RK4 integration requires four iterations per time step for the calculation of difference terms and update of state variables. Together, these requirements may result in excessively long simulation execution times (e.g. 3 min, real time), depending on the number of simulation objects, length of the simulation period, and computer processing capacity.

5.4. Analytical integration

Analytical integration methods can accommodate high rate, first-order processes at large time steps (e.g. 1 day) and can be used to minimize required calculations and simulation execution times. However, aquaculture facilities are typically characterized by simultaneous processes within and among facility units, and achievement of analytical solutions normally requires the use of simplifying assumptions. To explore tradeoffs between mathematical rigor and simulation processing times, combined numerical-analytical and simplified analytical integration methods were developed. For combined numerical-analytical integration, difference terms for each of the four cycles of RK4 integration are calculated using analytical integration. For simplified analytical integration, differential equations are simplified to a level where analytical solutions can be attained (Elliot, 1984). By this simplification, some simultaneous processes are unlinked, and thus simulation objects and the variables they contain are updated in order of their increasing dependence on other objects and variables. The simulation order used is facility climate, up to downstream facility units, and finally fish lots. In addition, variables within a facility unit are updated in order of increasing dependence on other variables, beginning with water temperature.

5.5. Management and simulation time steps

The size of the management time step is based on the desired management intensity, i.e. the time interval between successive, periodic tasks of the facility and
fish culture managers. The size of the simulation time step is based on the nature of the aquaculture system and temporal resolution required to adequately capture system dynamics. Daily simulations (e.g. 1-day time step), for which diurnal variables and processes are expressed and used as daily means, always represent some level of simplification at a degree depending on the type of facility and analysis resolution level. For example, all fish culture systems are at least characterized by diurnal fish process, resulting from day-versus-night activity levels and feeding rates of fish. However, diurnal simulations (e.g. 1-h time step) are required only when the variability of process rates and state variables within a day period, and associated management responses, must be considered to adequately represent the system. For example, diurnal simulations may be used for solar-algae ponds for high-resolution modeling of heat transfer and primary productivity, and they may be used for intensive systems for high-resolution modeling of fish feeding and metabolism. Any consideration of process management within a 24-h period requires diurnal simulations, e.g. pre-dawn aeration for pond-based systems or diurnal control of oxygen injection rates for intensive systems. For RK4 integration, daily simulations may require time steps of less than one day, but variables and processes are still used as daily means.

6. AquaFarm testing, calibration, and validation

The program code modules comprising AquaFarm were tested, debugged, and verified to perform according to the previously reported or newly developed methods from which they were developed. Testing alone was sufficient to validate data input and output, management, and display tasks, integration procedures for differential equations, and simulation of facility management. Similarly, the validity of actively managed processes was largely dependent on given process specifications (e.g. water treatment efficiencies) and confirmed by direct testing. Finally, AquaFarm was verified to provide full ranges of expected results (dependent variables) for all types of extensive and intensive aquaculture systems, solely by adjustment of input parameters and independent variables over their reasonable ranges. In sum, this testing verified the internal and external consistency of AquaFarm (Cuenco, 1989) and indicated sufficient development of the collected parameters, variables, and unit processes considered and their combined expression as differential equations and integrated functions.

Requirements for calibration and validation of the component models (Cuenco, 1989) used in AquaFarm was variable, depending on the nature of these models and their level of development in the supporting literature. Calibration is the process of determining values for model parameters (equation coefficients and exponents) through regression procedures using empirical datasets. Due to the wide use of mechanistic models in AquaFarm, most parameters have inherent meaning with respect to the processes they represent and can be directly estimated using reported values. Validation is the process of testing how much confidence can be placed on simulation results. Calibration and validation accomplishments to date
are given in Appendix A. For some component models, these accomplishments are preliminary and/or rely on parameter values from the supporting literature. Completion of calibration and validation procedures for selected, unit process models is ongoing, as described in the conclusion to this paper.

7. AquaFarm application

Application of AquaFarm to various aquaculture systems and analyses is demonstrated in the following examples. For each exercise, site-specific facility variables, management strategies, and model parameters were entered into AquaFarm. Additional parameters of unit process models were based on default values provided by AquaFarm. Simulations were then performed to generate fish culture schedules, chronologies of facility state variables and processes, and required resources to achieve fish production objectives. Finally, predicted performance data were compared to empirical data from representative studies in the literature.

Reporting of the specifications and results of these simulation exercises is limited to overviews, with a focus on core issues of fish performance and dominant facility processes. The specifications and results presented are not necessarily meant to represent critical variables, but rather to illustrate the range of detail and analytical capacities available in AquaFarm. The design procedure presented earlier is not demonstrated, rather the results of a single simulation are presented for each system type. Enterprise budgets are not presented, for which unit costs are highly specific to location and budget formats have already been described. While not shown, however, any of these examples could use a series of simulations to consider resource use, management intensity, and budgetary requirements over a range of fish production levels and alternative design and management strategies.

For all of these exercises, it is emphasized that the accuracy of simulation results relative to empirically determined results was highly dependent on the accuracy of site-specific variables and parameters. When simulation results are said to be ‘comparable’ to the referenced studies, it is meant that simulation results were within the range of reported results and showed similar cause-and-effect behavior for independent and dependent variables. Conclusions for these exercises include the caveat that fully comprehensive reporting of methods and results were not available in the studies used, as is typical in technical papers, requiring the estimation of some design and management variables.

In these simulation exercises, results showed close agreement between simplified analytical integration and rigorous numerical (RK4) integration for a variety of system types, using time steps of 1 day for daily simulations and 1 h for diurnal simulations. For daily simulations especially, in which state variables (as daily means) normally change relatively slowly over time, simplifications used to uncouple simultaneous processes so that analytical solutions could be achieved were clearly supported. Combined analytical-numerical integration was successful in achieving considerably larger time steps than allowed by purely numerical integration.
7.1. Tilapia production in ponds

AquaFarm was applied to the production of Nile tilapia (*Oreochromis niloticus*) in tropical (10° latitude) solar-algae ponds. Specifications and results of this exercise are provided in Table 6 and Figs. 5, 6, and 7. Diurnal simulations were used and water stratification was considered. Agriculture limestone (calcium carbonate) and fertilizer were applied to maintain DIC (in terms of alkalinity), DIN, and DIP nutrient levels for primary productivity. Fertilized ponds received lime and fertilizer only. Fertilized-fed ponds received lime and fertilizer by the same management criteria as fertilized ponds, with additional application of pelletized feed as required to achieve target fish growth rates. Fertilizer consisted of combined chicken manure and ammonium nitrate, with the latter added to achieve a nitrogen-phosphorous ratio of 5.0, based on the manure nitrogen and phosphorous contents (Lin et al., 1997).

Predicted water quality regimes and fertilizer and feed requirements were comparable to reported values for tilapia production under similar site and management conditions. As expected, total lime application rates were in the low range of reported rates (Boyd, 1990; Boyd and Bowman, 1997), for which pond source water had low alkalinity but soils were assumed to already be neutralized with respect to exchange acidity (base unsaturation). The nitrogen and phosphorous application rates used were within reported ranges for tilapia production in fertilized ponds, which range 2.0–4.0 kg N ha\(^{-1}\) day\(^{-1}\) at N:P ratios that range 1:1–8:1 (Lin et al., 1997). For fertilized and fertilized-fed ponds, simulated fish growth rates and total production per hectare, fish density level at the onset of feeding, and required feed application rates were comparable to reported results (Diana et al., 1996; Diana, 1997; Lin et al., 1997). Fish production and application of fertilizer and feed were adequately estimated using a daily time step with no consideration of water stratification. However, as generally found for solar-algae ponds, diurnal simulations and consideration of stratification were required to estimate extremes in water quality regimes. Typical diurnal profiles of temperature and dissolved oxygen, as shown in Fig. 7 for mid summer, were comparable to reported profiles for stratified tropical ponds (Losordo and Piedrahita, 1991; Piedrahita et al., 1993; Culberson and Piedrahita, 1994). The maximum divergence in water quality between the top and bottom layers was controlled by the specified regime of daily-minimum layer mixing rates.

7.2. Catfish production in ponds

AquaFarm was applied to production of channel catfish (*Ictalurus punctatus*) in temperate (30° latitude) solar-algae ponds. Specifications and results of this exercise are provided in Table 7 and Figs. 8, 9, and 10. Diurnal simulations were used and water stratification was considered. Single fish stocking and harvest events were used to simplify this example, rather than the periodic high-grade harvesting and partial re-stocking methods typically employed for catfish production. Target fish numbers and weights were specified such that feed application rate increased to a maximum of 110 kg ha\(^{-1}\) day\(^{-1}\), in order to emulate conditions used in Cole and Boyd...
Table 6
Example application: tilapia production in fertilized and fed ponds

**Specifications**

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location: 10 N latitude; 10 m elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weather: annual regimes for air temperature, cloud cover, precipitation, and water mixing index (stratification)</td>
</tr>
<tr>
<td></td>
<td>Source water quality: 20 mg l⁻¹ alkalinity and equilibrium gas concentrations</td>
</tr>
<tr>
<td>Cultural systems</td>
<td>Levee type, clay lined ponds, 1.0 ha in area, and 1.0 m average depth</td>
</tr>
<tr>
<td></td>
<td>Water makeup to replace losses and maintain depth</td>
</tr>
<tr>
<td></td>
<td>Pond unit processes used: water budget, passive heat transfer, seasonal water stratification, passive gas transfer, solids settling, primary productivity, bacterial processes (organic oxidation, nitrification, and denitrification), soil processes, and fish processes</td>
</tr>
<tr>
<td></td>
<td>Fertilizer composition: chicken manure with ammonium nitrate added to achieve an N:P ratio of 5.0, with a combined composition of 22.4% N, 4.48% P, and 70% dry wt. organic solids</td>
</tr>
<tr>
<td></td>
<td>Feed composition: 35% protein, 1.5% phosphorous</td>
</tr>
<tr>
<td></td>
<td>Fertilized ponds (see Table 1 for units): agricultural limestone and mixed inorganic/organic fertilizer applied to maintain DIC (alkalinity ≥ 40), DIN (≥ 1.0), and DIP (≥ 0.1), beginning 6 weeks prior to fish stocking</td>
</tr>
<tr>
<td></td>
<td>Fertilized-fed ponds: additional application of prepared feed as required to achieve target fish growth rates</td>
</tr>
<tr>
<td>Fish production objectives</td>
<td>Culture period: March 1 to Oct. 1 (215 days)</td>
</tr>
<tr>
<td></td>
<td>Fish number: 10 000–9000 fish ha⁻¹ at 10% mortality</td>
</tr>
<tr>
<td></td>
<td>Fish weight: 1.0 g at stocking to weight available on Oct. 1 for fertilized ponds, and 1.0–512 g target weight for fertilized-fed ponds</td>
</tr>
</tbody>
</table>

**Results**

| Fish production          | Fertilized pond applications: total lime applied 1870 kg ha⁻¹, fertilizer applied at a mean rate of 12.3 kg ha⁻¹ d⁻¹ (2.8 kg N ha⁻¹ day⁻¹ and 0.55 kg P ha⁻¹ day⁻¹) over the pond pre-conditioning and fish rearing period |
|                         | Fertilized-fed pond applications: total lime applied 1900 kg ha⁻¹, fertilizer requirements reduced about 10%, supplemental feed applied at an increasing rate to a maximum of 65 kg ha⁻¹ day⁻¹ over a 70-day end period |
|                         | Fertilized pond production: 332 g fish at 3000 kg fish ha⁻¹ on Oct. 1 |
|                         | Fertilized-fed pond production: 512 g fish at 4600 kg fish ha⁻¹ on Oct. 1, 80% fish feeding index (% maximum ration) to achieve target weight, and 170% food conversion efficiency (based on applied feed only, mortality included) |
|                         | Fertilized pond water quality (for fish culture period, including diurnal and stratification extremes; see Table 1 for units): temperature 22–34; DO 2.8–14.5; pH 7.0–9.5; DC 0.01–7.8; NO₃ 0.60–0.74; TAN 0.25–0.53, NH₄ 0.01–0.25; phytoplankton 8.5–10.8; NPP – 0.5–6.0 (whole column) |
|                         | Fert.-fed pond water quality (for fish culture period, including diurnal and stratification extremes; see Table 1 for units): similar to fertilized pond, except DO 1.6–14.5; pH 6.9–9.5; DC 0.01–10.3 |
Fig. 5. Simulated data (1-h time step) for tilapia production in fertilized ponds over a 7-month culture period. The temperature band represents the diurnal temperature regime. Critical standing crop (CSC, 1600 kg ha\(^{-1}\)) with respect to natural food resources occurs at the peak FBP and inflection point of fish growth rate.

Fig. 6. Simulated data (1-h time step) for tilapia production in fertilized and fed ponds over a 7-month culture period. The temperature band represents the diurnal temperature regime. Critical standing crop (CSC, 1600 kg ha\(^{-1}\)) with respect to natural food resources is achieved, followed by a short decline in FBP until the onset of supplemental feeding.

(1986) and Tucker and van der Ploeg (1993). Aeration was used as required to maintain bottom-layer dissolved oxygen above a minimum level (30% saturation), for which aerator specifications were matched to Cole and Boyd (1986). The
production period, from June 1 year 1 to October 31 year 2 (519 days), included a fish over-wintering period.

Feed application rates increased over the rearing period in association with increasing fish biomass density as well as varying with water temperature. Fish feeding and growth rates were within typical ranges (Tucker, 1985). Predicted water quality regimes and aeration requirements were comparable to reported values for catfish production, including aeration timing, maximum power requirement, and cumulative power use (Cole and Boyd, 1986; Brune and Drapcho, 1991; Tucker and van der Ploeg, 1993; Schwartz and Boyd, 1994). To match reported aeration requirements (Cole and Boyd, 1986), accurate specifications were required for aerator size, standard aerator efficiency, and minimum allowed dissolved oxygen levels.

7.3. Shrimp production in ponds

AquaFarm was applied to semi-intensive production of marine (penaeid) shrimp in tropical (10° latitude), fertilized, fed, and aerated solar-algae ponds. Results of this exercise (not shown) compared well to marine shrimp production studies (Fast and Lester, 1992; Wyban, 1992; Briggs and Funge-Smith, 1994), including shrimp growth, aeration requirements, and water quality regimes. For estimating natural food resources and timing the initiation of prepared feed application, empirically based critical standing crop (e.g. 100–300 kg ha$^{-1}$) and carrying capacity shrimp densities were used without consideration of NPP, given the benthic location and variety of food resources utilized by shrimp. Pond water exchange rates of 0.0–30%
Table 7
Example application: channel catfish production in ponds

| Specifications | Location: 32 N latitude, 100 m elevation  
Weather: annual regimes for air temperature, cloud cover, precipitation, and water mixing index (stratification)  
Source water quality: 100 mg l⁻¹ alkalinity and equilibrium gas concentrations |
| --- | --- |
| Facility | Levee type, clay lined ponds, 5.0 ha in area, and 1.0 m average depth  
Water makeup to replace losses and maintain depth  
Pond unit processes used: water budget, passive heat transfer, seasonal water stratification, passive and active gas transfer, solids settling, primary productivity, bacterial processes (organic oxidation, nitrification, and denitrification), soil processes, and fish processes  
Aeration: on at ≤30% and off at ≥40% DO saturation based on water quality of bottom water layer, maximum aeration rate 6.25 kW ha⁻¹, and aerator SAE 1.2 kg O₂ kWh⁻¹ |
| Culture systems | Culture period: June 1, year 1 to Oct. 31, year 2 (518 days)  
Fish number: 12 000 to 10 500 fish ha⁻¹ at 12.5% mortality  
Fish weight: 1.0 g at stocking to 880 g target weight |
| Fish production objectives | Fish feeding index (% maximum ration)  
50% food conversion efficiency  
9250 kg ha⁻¹ maximum fish biomass density  
110 kg ha⁻¹ day⁻¹ maximum feed application rate  
Aeration power use: total of 4260 kWh ha⁻¹, for 672 total hours of operation, ranging from 2 to 7 h per day, over a period of 4 months  
Water quality (see Fig. 8 and Fig. 9): DIN averaged 72% TAN and 28% nitrate, alkalinity 80–100 mg l⁻¹, and diurnal NPP 0.4–5.0 g C m⁻³ day⁻¹ (whole column) |

Results

- 80% fish feeding index (% maximum ration)
- 50% food conversion efficiency
- 9250 kg ha⁻¹ maximum fish biomass density
- 110 kg ha⁻¹ day⁻¹ maximum feed application rate
- Aeration power use: total of 4260 kWh ha⁻¹, for 672 total hours of operation, ranging from 2 to 7 h per day, over a period of 4 months
- Water quality (see Fig. 8 and Fig. 9): DIN averaged 72% TAN and 28% nitrate, alkalinity 80–100 mg l⁻¹, and diurnal NPP 0.4–5.0 g C m⁻³ day⁻¹ (whole column)

per day were simulated and compared, including impacts on pond water quality, tradeoffs in relation to aeration requirements, and compound and BOD loading rates on receiving waters.

Regarding shrimp biomass density constraints with respect to dissolved oxygen, it has been suggested that while air-water gas exchange limits production of finfish such as tilapia and catfish, advective transport of oxygen through the water column to the benthic region limits production of bottom dwelling shrimp (Garcia and Brune, 1989; Brune and Drapcho, 1991). Simulation results indicated that consideration of this proposed 'diffusive boundary layer' in which the shrimp reside, located in the bottom few centimeters of the water column, was required to achieve reported aeration rates for shrimp ponds. This boundary layer is not considered in the two-layer thermal stratification model used in AquaFarm, it acts in addition to
thermal stratification, and it is present in aerated/mixed ponds where thermal stratification is broken down. Therefore, it was accounted for by the minimum dissolved oxygen criterion used for aeration management. By increasing this

Fig. 8. Simulated data (1-h time step) for catfish production in fed ponds, showing the last 7 months of the 17 month culture period. Bands for water quality variables represent diurnal, stratified regimes, and top and bottom layers of the water column are shown for temperature and dissolved oxygen. Bottom bands overlay top bands to a large degree and daily water-column turnover is occurring.

Fig. 9. Simulated data (1-h time step) for catfish production in fed ponds, showing the last 7 months of the 17 month culture period. Bands for water quality variables represent diurnal, stratified regimes, for which means of the top and bottom layers of the water column are shown and daily water-column turnover is occurring (see Table 1 for definitions of variables).
Fig. 10. Simulated oxygen budget data (1-h time step) for catfish production in fed ponds, for a few days in late August in the last 7 months of the culture period and in the vicinity of peak feeding and NPP rates. Diurnal, water column stratification and turnover are occurring, for which top and bottom layers for NPP and BR are shown. Budget items include passive and active gas transfer (PGT and AGT), net primary productivity (NPP), bacterial respiration (BR), and fish oxygen consumption.

criterion, the concentration gradient necessary to transfer oxygen into the benthic boundary layer was provided and aeration power requirements were increased.

7.4. Salmon production in tanks and cages

AquaFarm was applied to Atlantic salmon (Salmo salar) production, including egg incubation, production of 45.0 g smolts in single-pass, flow-through tanks, and production of 4.0 kg marketable fish in seawater cages. Specifications and results of this exercise are provided in Table 8 and Figs. 11 and 12. Egg, smolt, and growout production stages were linked by their temporal sequence and population numbers, for which dates and population numbers were given for the input of fertilized eggs and output of harvested fish. Based on the intermediate target date for first-feeding fry, egg incubation was controlled by adjusting water temperatures to an increasing 8–10°C regime using water blending. Smolt and harvest target fish weights were achieved through control of feed application rates.

This example demonstrates some of the detail that can be used in fish lot management, but results of multiple fish lots are not shown. Results were comparable to production data given in Laird and Needham (1988). Accurate estimations for expected source water quality and temperature regimes and assumed water exchange rates of cages were critical inputs for this exercise, in which unit processes of smolt tanks and salmon cages were dominated by fish metabolism and water advection. This example demonstrates the use of biomass densities and water exchange rates as management criteria. Alternatively, required water flow rates and
Table 8
Example application: Atlantic salmon production in tanks and cages

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Facility</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Location: 57 N latitude, 0 m elevation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weather: annual regimes for air temperature and cloud cover</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Source water quality: annual water temperature regimes, 50 mg l$^{-1}$ alkalinity for freshwater, 100 mg l$^{-1}$ alkalinity and 35 ppt salinity for seawater, and equilibrium gas concentrations</td>
<td></td>
</tr>
<tr>
<td>Culture systems</td>
<td>Egg incubators: parallel configuration, water flow rates at 2.0 l min$^{-1}$ per 10 000 eggs and 5.0 l min$^{-1}$ per 10 000 alevin (hatched fry)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Smolt tanks: 10 m$^3$ cylindrical tanks, parallel configuration, maximum fish density 30 kg m$^{-3}$, and water retention time 30 minutes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Growout cages: 1500 m$^3$, cylindrical, seawater cages, maximum fish density 22 kg m$^{-3}$, and assumed water retention time 1.0 h</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fish production objectives</th>
<th>Stage</th>
<th>Dates</th>
<th>Number</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Egg to first-feeding fry</td>
<td>Jan. 21, year 1 to May 1, year 1 (100 days)</td>
<td>15 000–12 000</td>
<td>Egg to 0.2 g</td>
</tr>
<tr>
<td></td>
<td>Fry to smolt</td>
<td>May 1, year 1 to May 1, year 2 (365 days)</td>
<td>12 000–6600</td>
<td>0.2–45.0 g</td>
</tr>
<tr>
<td></td>
<td>Smolt to harvest</td>
<td>May 1, year 2 to Oct. 1, year 3 (520 days)</td>
<td>10 000–8500</td>
<td>45.0–4000 g</td>
</tr>
</tbody>
</table>

Egg: 20% mortality
Smolt: 5% cull removal at 0.75 g fish; 5% cull removal at 2.0 g fish; 75% high-grade for potential yearling smolts at 10.0 g fish; 10% mortality, and 48% protein feed
Growout: no handling other than harvest; 15% mortality, and 45% protein feed

Results

Smolt production
Each smolt tank was stocked from the output of one egg incubator
Total fish loss due to mortality and low-grade removal required an initial 12 000 fish per tank to achieve a final target smolt density of 30 kg m$^{-3}$
70% fish feeding index (% maximum ration) and 67% food conversion efficiency (includes cull and mortality losses)
Maximum fish respiration rate: 170 mg O$_2$ kg fish$^{-1}$ h$^{-1}$
Water quality (see Table 1 for units): DO $\geq$77% sat.; DC $\leq$35% sat.; TAN $\leq$0.30; NH$_3$ $\leq$0.003; pH 7.7–8.2; and particulate solids $\leq$2.9

Cage growout
Each cage was stocked with the output of 1.5 smolt tanks
Total fish loss due to mortality required an initial 10 000 smolts per cage to achieve a final target fish density of 22 kg m$^{-3}$
90% fish feeding index (% maximum ration) and 52% food conversion efficiency (includes mortality losses)
Water quality (see Table 1 for units): DO $\geq$ 65% sat.; DC $\leq$178% sat.; TAN $\leq$0.37; NH$_3$ $\leq$0.005; pH 8.0–8.2; and particulate solids $\leq$3.5
Total compound loading on supporting water body per 1000 kg fish produced: 680 kg dry wt. solids; 750 kg BOD; 80 kg DIN; and 20 kg DIP
allowed biomass loading rates could have been based on water quality variables such as dissolved oxygen, COC, carbon dioxide, and un-ionized ammonia.

7.5. Salmon production using serial water reuse

AquaFarm was applied to hatchery production of spring chinook salmon (*Oncorhynchus tshawytscha*) utilizing serial raceways, pure oxygen absorbers be-
tween raceways, and water reuse. Specifications and results of this exercise are provided in Table 9 and Figs. 13 and 14. The purpose of this example is to demonstrate the simulation of diurnal fish metabolic rates resulting from feed application during daylight hours and diurnal temperature oscillations. Such considerations can be applied to any type of aquaculture system, when it is desired to account for impacts of diurnal fish metabolism on water quality. Parameters used for modeling fish feeding and metabolic rates were calibrated using empirical data for a given week, with the calibrated model then applied to the following week at the same hatchery.

Results were comparable to production data given in Ewing et al. (1994) and additional, unpublished, continuous monitoring data from spring chinook hatcheries in the same region. Fish rearing-unit processes were dominated by fish metabolism and water advection, a relatively simple modeling exercise. This example demonstrates the use of diurnal simulations to assess daily peak loading rates of fish biomass support and cumulative impacts of fish metabolism on water quality under serial water reuse. This type of exercise can be used to assess impacts of management variables on water quality, including fish biomass loading, oxygen injection rates by constant or demand-based process control, and temporal distribution of feeding events over daylight hours. Based on management tolerance for short term, sub-optimal water quality, daily peak-mean ratios of fish biomass support requirements (Colt and Orwicz, 1991b) can then be derived for use in simulations using daily time steps. Daily peak-mean ratios are applied to management variables such as water flow rates of fish rearing units.

Table 9

Example application: spring chinook production in raceways

<table>
<thead>
<tr>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: 45 N latitude, 370 m elevation</td>
</tr>
<tr>
<td>Weather: annual parameters for air temperature and cloud cover</td>
</tr>
<tr>
<td>Source water quality: annual temperature regimes, 20 mg l$^{-1}$ alkalinity, and equilibrium gas concentrations</td>
</tr>
<tr>
<td>Culture systems</td>
</tr>
<tr>
<td>Pure oxygen absorbers placed between raceways, with automated oxygen addition rates based on a 100% saturation set-point</td>
</tr>
<tr>
<td>Three 105 m$^3$ raceways per series, operated at a raceway water retention time of 1 h and 6 kg m$^{-3}$ fish density at the given fish size</td>
</tr>
<tr>
<td>Fish production objectives</td>
</tr>
<tr>
<td>Fry to pre-smolt growout: culture period for purposes of this exercise limited to June 1–10, with 222,000, 2.5 g fish per raceway on June 1 and using 50% protein feed</td>
</tr>
<tr>
<td>Results</td>
</tr>
<tr>
<td>Fish production</td>
</tr>
<tr>
<td>Mean values for 10 day analysis period: 2.9 g fish weight, 6.1 kg m$^{-3}$ fish density, 3.7% bw per day feeding rate, 85% food conversion efficiency</td>
</tr>
<tr>
<td>Fish respiration rate: 200–480 mg O$_2$ kg fish$^{-1}$ h$^{-1}$, showing diurnal, sinusoidal profiles in rates and resulting impacts on water quality</td>
</tr>
</tbody>
</table>
Fig. 13. Simulated data (smooth lines; 1-h time step) and empirical data (jagged lines; continuous monitoring) for Pacific salmon hatchery production in raceways, showing a single day (June 1) within the culture period. Data points shown for feeding represent time of feeding and feeding rates, and an association between feeding times and peaks in OC are evident (see Table 1 for definitions of variables).

Fig. 14. Simulated data (1-h time step) for Pacific salmon hatchery production in three, serial raceways (numbered 1, 2, and 3, up to down stream), showing a few days at the beginning of June within the culture period. Oxygen is added between raceways so that influent DO levels of raceways are equal but fish metabolites are shown to be accumulating (see Table 1 for definitions of variables).

7.6. Fish production using water recirculation

AquaFarm was applied to the intensive production of rainbow trout (Heinen et al., 1996), hybrid striped bass (Tuncer et al., 1990; Singh et al., 1997), and tilapia
(Rosati et al., 1997; Twarowska et al., 1997) in semiclosed (e.g. 2.0 system exchanges per day) and minimal-exchange (e.g. 0.075 system exchanges per day) water recirculation systems. As described in the listed references, major systems components included: (1) fish rearing units, including rectangular cross flow and single and dual drain circular and polygonal tanks; (2) sump tanks and pumps; (3) water heaters; (4) aerators and oxygenators; (4) carbon dioxide strippers; (6) particle separators, parallel-tube settling basins, expandable granular media filters (bead filters), and microscreen filters for solids removal; (7) trickling, fluidized bed, and expandable granular media biofilters for nitrification; (8) alkalinity control by addition of various carbonate compounds; (9) water disinfection units; and (10) settling basins for discharged water/solids. An example facility map is shown in Fig. 3, for which redundant, parallel water treatment units are used singularly or together depending on water flow rate. Additional passive processes required to model these systems included heat transfer under controlled climates, gas transfer, solid settling, bacterial oxidation of organic solids, and nitrification and denitrification. AquaFarm was also applied to tilapia and catfish production in green water (phytoplankton present) recirculation systems (Drapcho and Brune, 1989; Cole et al., 1997; Lutz, 1997; Avnimelech, 1998). These systems varied widely in design but essentially consisted of intensively fed fish rearing units, coupled with one or more facility units for growth and/or harvesting of algae, oxidation of particulate solids, settling and physical removal of particulate solids, gas exchange, and water transport.

For each of these systems, a facility was constructed according to the supporting study, using estimated specifications when facility design and management were not sufficiently reported. Results of these exercises (not shown) were generally comparable to reported results, including fish production, solid waste production and composition, consumption of resources (e.g. energy, water, feed, oxygen, and alkalinity compounds), and water quality regimes. However, comparisons between simulated and reported results were limited by a lack of sufficient reporting detail in the studies used. In contrast to extensive systems, simulation results were largely a function of facility unit specifications (e.g. oxygenators, biofilters, and solid filters) and were less dependent on parameters of passive unit processes. These actively managed unit processes are modeled in terms of their given efficiencies. For example, oxygen absorption efficiencies for oxygenators, nitrification efficiencies for biofilters, and solid removal efficiencies for solid filters are specified, rather than calculating these efficiencies from a host of additional facility unit specifications.

8. Conclusion

8.1. Development status of AquaFarm

The purpose of this paper has been to provide an overview of the components, methods, and capacities of AquaFarm, a simulation and decision support system
for aquaculture design and management planning. A comprehensive description of the methods and application of AquaFarm is available in Ernst (2000b). Decision support is accomplished through the provision of expertise in a variety of disciplines and the processing of computationally intensive analyses, as typically encountered in system-level aquacultural engineering. Due to the considerable level of work required in the development of AquaFarm, a staged development approach is being used. The first stage of this development, as described in this paper, consists of the partitioning of aquaculture systems into functional components and the flexible recombination of these components into system-level simulation models and design procedures. Additional development stages currently in progress consist of ongoing validation concerns, user testing, and incorporation of user feedback.

The methods and results presented indicate that AquaFarm provides useful and sufficiently accurate decision support functionality. This conclusion is based on: (1) the use of published, generally accepted modeling and simulation procedures; (2) full user access to input parameters and variables and an assumed level of user responsibility for input data; and (3) the successful completion of extensive testing and a wide range of simulation exercises. Because AquaFarm was primarily developed from the existing literature, it is assumed reasonable that some burden of proof can be placed on this literature. At the least, AquaFarm supports many of the engineering analyses that would otherwise be used, with the benefit of computerization of these tasks. However, AquaFarm will not be widely released until completion of additional validation and user testing.

8.2. Continued development of AquaFarm

A number of development tasks are in progress to quantify the degree of confidence that can be placed on predicted facility performance variables and to alleviate or assist user responsibilities where possible. Prioritized objectives of these tasks are to:

1. Complete sensitivity studies and validation procedures for selected component models and combined models (facility models).
2. Provide pre-designed, exemplary facilities, for a range of aquaculture system types, that can be used as a starting point for new projects or tutorials for new users.
3. Establish a base of selected users from aquaculture education, development, and production. Based on their feedback, assess and improve the capacity of AquaFarm to address user needs, present reasonable levels of user responsibility, and provide a navigable interface.
4. Provide interface navigation aids to help guide users through project specification, simulation, and evaluation procedures.
5. Provide capabilities within AquaFarm to derive parameters for fish performance models from user supplied datasets.
As discussed earlier, the simplifying assumptions and aggregated processes used in aquaculture modelling make it difficult to derive a single set of parameter values that provides sufficient simulation accuracy for all culture conditions of a given aquaculture species. This problem can be addressed by providing capabilities to utilize user-supplied datasets (e.g. historical fish production and water quality) for the derivation of site-specific model parameters. Initially, this effort will concentrate on fish performance, due to its central role in facility design, management, and resource and enterprise budgets. In addition, AquaFarm is being used to perform sensitivity studies in order to rank input parameters and variables with respect to their level of impact on simulation results. This will show where calibration and validation procedures should be concentrated and where user responsibilities for accurate input data are most pronounced.

Given the scope and resolution of AquaFarm, required levels of work and supporting data for calibration and validation procedures are considerable and present an ultimate constraint to this endeavor. Ideally, these datasets should include complete descriptions of environmental conditions, system components, management protocols, and resulting fish and facility performance variables. Practically, however, such datasets are not readily available. For intensive, water reuse and recirculating aquaculture systems, most available research has been conducted on individual unit processes or system components and calibration and validation efforts must often proceed at this level. System level studies are available in the literature, mainly as technical papers, but generally lack sufficient reporting of methods and results for detailed calibration and validation procedures. In contrast, for extensive and semi-intensive, pond based aquaculture, publicly available databases are available and their usefulness in the development of pond simulation models and decision support systems has been demonstrated (e.g. Froese and Pauly, 1996; Piedrahita et al., 1997; Ernst et al., 1997; Ernst and Bolte, 1999; Nath et al., 2000). In addition, many technical papers available for pond based aquaculture contain fairly comprehensive reporting of methods and results, given that their scope can normally be limited to ponds with no need to consider water transport and treatment systems. However, results from pond studies can also be more difficult to interpret, given the stochastic nature of these systems, the difficulty of isolating individual unit processes (e.g. components of oxygen mass balances), and the difficulty of monitoring site-specific conditions and processes such as pond micro-climates, soil processes, sediment accumulation, and water seepage. The authors gratefully acknowledge the support provided by Sea Grant (National Oceanic and Atmospheric Administration, US Dept of Commerce; project no. R/Aq-42) and the Bonneville Power Administration (US Dept of Energy; project no. DE-FC79-89BP03024) and indirect support provided by the Pond Dynamics/Aquaculture Collaborative Research Support Program (US Agency for International Development).

Appendix A. Domain expert methods

A.1. Aquatic chemist: methods, application, and validation
A.1.1. Physical Properties of Water

A.1.1.1. Methods. Water density and specific weight (Millero and Poisson, 1981), heat capacity (Millero et al., 1973), vapor pressure (Green and Carritt, 1967), dynamic and kinematic viscosity (Millero, 1974), and latent heat of vaporization (Brooker, 1967) are calculated as function of water temperature and salinity.

A.1.1.2. Application. Properties are used in physical process models.

A.1.1.3. Validation. Calculated property values were equivalent to values in the listed references for temperatures of 0–40°C and salinities of 0–40 ppt.

A.1.2. Dissolved gas equilibria

A.1.2.1. Methods. Equilibria concentrations of nitrogen, oxygen, and carbon dioxide gases are a function of water temperature and salinity and gas-phase composition and total pressure (Colt, 1984). Gas saturation levels are based on equilibria and existing gas concentrations.

A.1.2.2. Application. Equilibria concentrations are used in gas mass balances. Gas saturation levels are used for interpreting and reporting water quality.

A.1.2.3. Validation. Calculated equilibria values were equivalent to values in Colt (1984) for temperatures of 0–40°C, salinities of 0–40 ppt, air and pure-oxygen gas phases, and full ranges in elevation, barometric pressure, water depth, and hydrostatic pressure.

A.1.3. Acid-base and precipitation-dissolution chemistry

A.1.3.1. Methods. Equilibrium pH and compound specie concentrations are a function of total compound concentrations, water temperature, and water salinity (Snoeyink and Jenkins, 1980; Stumm and Morgan, 1981; Butler, 1982; Fritz, 1985). Solutions for equilibrium conditions are based on equilibrium, mass balance, and charge balance equations and presence of a carbon dioxide gas phase and/or calcium carbonate solid phase, solved by numerical methods. Derivations of these functions are used to calculate required quantities of acid-base compounds for alkalinity and pH adjustment. Compounds participating in acid-base and precipitation-dissolution chemistry are listed in Table 1.

A.1.3.2. Application. Equilibria values are used for water quality interpretation and reporting, ionization fraction terms in mass balance equations, and determination of pH levels after addition and removal of acid-base compounds and carbon dioxide. Alkalinity and pH adjustment to specified levels can be used for static or flowing water.
A.1.3.3. Validation. Calculated equilibria values were equivalent to values in the listed references for temperatures of 0–40°C, salinities of 0–40 ppt, full ranges of compound concentrations, and presence of carbon dioxide and calcium carbonate phases. Alkalinity and pH adjustments using a variety of compounds were verified. Example problems in the listed references were successfully completed.

A.2. Aquacultural engineer: methods, application, and validation

A.2.1. Facility climate

A.2.1.1. Methods. Climate variables include daily mean solar radiation, air temperature, precipitation, wind speed, relative humidity, cloud cover, time of sunrise and sunset, day length, and diurnal regimes of solar radiation and air temperature. Predicted annual and diurnal regimes of climate variables are: (1) interpolated from user-supplied historical datasets; (2) defined by controlled climates; or (3) calculated as a function of facility latitude and altitude, seasonal parameters, and time of year and day (Card et al., 1976; Fritz et al., 1980; Kreider and Kreith, 1981; Straskraba and Gnauck, 1985; Hsieh, 1986; Nath, 1996).

A.2.1.2. Application. Climate variables are used for heat and gas transfer, water stratification, water budgets, primary productivity, and fish culture day length.

A.2.1.3. Validation. Generation of historically based and controlled climates was validated by testing. For calculated climates: (1) times of sunrise, sunset, and day lengths were equivalent to values in the listed references; (2) solar radiation values approximated values in the listed references given that sufficiently accurate cloud cover values were used; and (3) remaining variables corresponded to specified seasonal parameters.

A.2.2. Passive and active heat transfer

A.2.2.1. Methods. Heat energy transfer modes include solar and long wave radiation, water evaporation and flow, and heat convection-conduction at air-water, air-wall-water, and heater/chiller-water interfaces. Heat transfer with soil is not considered. Heat transfer rates are a function of climate variables and facility unit (1) water volume and flow rate; (2) air-water and air-wall-water surface areas; (3) wall dimensions and materials; and (4) heat transfer rates of heaters and chillers (Henderson and Perry, 1976; Welty et al., 1976; Fritz et al., 1980; Heisler, 1984; Midwest Plan Service, 1987; Creswell, 1993; Nath, 1996).

A.2.2.2. Application. Heat transfer rates are used in heat balances for prediction of water temperatures and calculation of energy requirements for heaters and chillers.
Heat transfer rates of each mode are individually quantified and available to the user as heat transfer budgets.

A.2.2.3. Validation. Example problems for tanks and pipes given in the supporting references were successfully completed (e.g. Henderson and Perry, 1976; Welty et al., 1976). Applications to outdoor fish ponds in tropical regions showed good fit to empirical water temperature data given the use of empirical climate data for the same period (Nath, 1996). Trial applications to outdoor fish ponds using calculated climate variables and water stratification showed reasonable agreement with reported annual temperature regimes.

A.2.3. Water thermal stratification

A.2.3.1. Methods. Water stratification is modeled using two (top and bottom) horizontal water layers of equal depth, in which mass and energy transfer processes are separately maintained for each layer and occur between layers (e.g. heat and gas transfer). Daily minimum layer mixing rates (% day$^{-1}$; water mixing index, WMI) are interpolated from given annual regimes of monthly mean values. Minimum mixing rates are increased as a function of layer water temperatures which result from passive heat transfer, and thus daily and seasonal water column turnover is considered.

A.2.3.2. Application. If water stratification is present, then facility units are modeled as two, inter-mixing water bodies with distinct state variables and unit processes.

A.2.3.3. Validation. Trial applications to outdoor fish ponds using calculated climate variables and WMI values of 1.0 (highly stratified) to 24.0 (unstratified) showed results comparable to reported temperature and dissolved oxygen depth-time profiles, including profile amplitude, shape, and seasonal changes (Losordo and Piedrahita, 1991; Piedrahita et al., 1993; Culberson and Piedrahita, 1994).

A.2.4. Water flow mechanics

A.2.4.1. Methods. Gravity and pressurized flow capacities for facility units and pump power requirements for pressurized systems are based on facility unit elevations (slope), dimensions, materials, pump and motor efficiencies, and serial/parallel configurations (Mott, 1979; Jensen, 1983). Water and air flow rates for airlift pumps are based on pump depth, lift, and diameter (Castro and Zielinski, 1980; Loyless and Malone, 1998). Facility units can have specific head loss considerations (e.g. media filters) and/or hydraulic loading constraints (e.g. biofilters and sedimentation basins).
A.2.4.2. Application. Water flow rate capacities and total dynamic head, net positive suction head, and energy (or compressed air) requirements of water pumping are used for water flow modeling, flow rate management, and water pump resource requirements.

A.2.4.3. Validation. Example problems given in the supporting references were successfully completed.

A.2.5. Water budgets

A.2.5.1. Methods. Facility unit water budgets (water mass balances) include influent and effluent flow rates, seepage infiltration and loss, precipitation and watershed runoff, and evaporation. Influent flow rate is a management variable, seepage is user specified, precipitation and evaporation are based on climate variables, and effluent flow rate is calculated from other water budget terms.

A.2.5.2. Application. Water budgets are used to manage influent flow rates, as required to maintain water depth (makeup) or overflow rate (exchange), and to quantify water resource requirements. The various water transfer routes listed above are considered in heat and compound transfer.

A.2.5.3. Validation. Applications to outdoor fish ponds in tropical regions showed good fit to empirical water budget data given the use of empirical climate data for the same period and sufficiently accurate seepage estimates (Nath and Bolte, 1998). For indoor systems, water budget terms in addition to influent and effluent flow can normally be ignored.

A.2.6. Passive and active gas transfer

A.2.6.1. Methods. Oxygen transfer coefficients for passive diffusion (gas-liquid phase diffusion) are a function of water depth, water velocity, and wind speed (Banks and Herrera, 1977; Rathbun, 1977; Tchobanoglous and Burton, 1991; Boyd and Teichert-Coddington, 1992). Oxygen transfer coefficients for active diffusion of air-contact units are a function of energy application rate, standard aeration efficiency (kg O₂ kWh⁻¹), and application conditions (Boyd and Watten, 1989; Colt and Orwicz, 1991a; Watten, 1994). Transfer coefficients for other gases (listed in Table 5) are calculated from oxygen coefficients by gas diffusivity transformations, consideration of air-film versus liquid-film diffusion constraints, and consideration of de/hydration rates for carbon dioxide (Thibodeaux, 1979; Stumm and Morgan, 1981; Grace and Piedrahita, 1994). For pure oxygen absorbers, gas transfer rates are based on oxygen absorption efficiency (%), oxygen transfer efficiency (kg O₂ kWh⁻¹), and gas stripping efficiencies for nitrogen and carbon dioxide (Watten et al., 1991; Watten, 1994).
A.2.6.2. Application. Gas transfer coefficients and rates are used in gas mass balances and to calculate power, compressed air, and oxygen requirements of gas exchangers.

A.2.6.3. Validation. For passive gas transfer, trial applications to exposed water bodies gave results comparable to reported dissolved oxygen and carbon dioxide regimes. For active transfer, method validity is largely dependent on given specifications of air-contact units and oxygen absorbers.

A.2.7. Solids settling (sedimentation)

A.2.7.1. Methods. Settling of particulate solids is based on water overflow rates (m day\(^{-1}\)) and velocities (cm s\(^{-1}\)) and particle settling velocities (m day\(^{-1}\)) and scouring velocities (cm s\(^{-1}\)) (James, 1984b; Tchobanoglous and Schroeder, 1985; Chen et al., 1994). A weighted-mean particle settling velocity is used according to contributing solid sources. Use of open media (e.g. biofilters and parallel tube/plate clarifiers), flow baffles, and dual-drain effluent configurations (Timmons et al., 1998) for solids management is accounted for in the specifications of individual facility units.

A.2.7.2. Application. Solid settling rates are used in solid mass balances and to quantify accumulation of settled solids in facility units, required solids removal from facility units, and facility solid waste production.

A.2.7.3. Validation. Method validity depends mainly on the accuracy of particle settling rates, for which the use of reported values gave reasonable results.

A.2.8. Solids filtration and fractionation

A.2.8.1. Methods. Filtration and fractionation of particulate solids by various types of mechanical filters are based on specified solid removal efficiencies (%) (Tchobanoglous and Schroeder, 1985; Chen et al., 1994; Timmons, 1994). Solids accumulating in filters are periodically removed, according to solid holding capacities and allowable pressure loss. Airflow rate requirements of fractionators are based on specified gas-liquid flow rate ratios.

A.2.8.2. Application. Solids filtration and fractionation rates are used in solid mass balances and to quantify accumulation of filtered solids, required solids removal from filters, and facility solid waste production.

A.2.8.3. Validation. Method validity depends on the accuracy of given solid removal efficiencies, which are highly specific to filter design and operation.
A.2.9. Chemical filtration

A.2.9.1. Methods. Removal of ammonium by ion-exchange and chlorine by adsorption is based on specified compound removal efficiencies (%) (Liao and Lin, 1981; Tchobanoglous and Schroeder, 1985). Filter media is periodically regenerated according to media compound capacity and any accumulation of solids.

A.2.9.2. Application. Compound filtration rates are used in compound mass balances and to quantify accumulation of filtered compounds and media regeneration requirements.

A.2.9.3. Validation. Method validity depends on the accuracy of given compound removal efficiencies, which are highly specific to filter design and operation.

A.2.10. Compound addition

A.2.10.1. Methods. Compound addition rates are based on set-point concentrations, compound purity (%) and solubility (%), and water flow rate (may be static water).

A.2.10.2. Application. Compound addition rates are used in compound mass balances and to calculate required compound quantities.

A.2.10.3. Validation. Method validity was confirmed by achievement of specified set-point concentrations for a variety of compounds, water quality conditions, and static and flowing water.

A.3. Aquatic biologist: methods, application, and validation

A.3.1. Soil processes

A.3.1.1. Methods. Soil processes consist of the combined physical, chemical, and biological uptake and release of compounds (listed in Table 5) across the soil-water interface (Boyd and Musig, 1981; Boyd, 1982, 1990; Eppes et al., 1989; Berthelson, 1993; Boyd and Bowman, 1997; Szabo and Olah, 1998; Steeby, 1998). Daily mean compound uptake (% day\(^{-1}\)) and release (g m\(^{-2}\) day\(^{-1}\)) rates are interpolated from given annual regimes of monthly mean values. Compound transfer due to water seepage is considered separately.

A.3.1.2. Application. Soil process rates are used in compound mass balances.

A.3.1.3. Validation. Method validity depends on the accuracy of given compound uptake and release rates, for which empirically based values are available in the listed references.
A.3.2. Bacterial processes

A.3.2.1. Methods. Bacterial processes include heterotrophic oxidation of organic solids, nitrification of ammonia and nitrite, and denitrification of nitrate (Fritz et al., 1979; Brune and Gunther, 1981; James, 1984a,d; Fritz, 1985; Tchobanoglous and Burton, 1991; Malone et al., 1993; Chen et al., 1993; Lu and Piedrahita, 1993; Wheaton et al., 1994a,b). Bacterial processes can occur in the water column, in settled solids, and on water-containment and filter-media surfaces. Consumption rates of primary substrates are a function of temperature, pH, and standard specific rates (day$^{-1}$ generally, and g TAN m$^{-2}$ day$^{-1}$ or g TAN m$^{-2}$ day$^{-1}$ ppm TAN$^{-1}$ for biofilters), using multiple substrate Michaelis–Menten kinetics. Consumption and excretion rates of additional compounds are based on metabolic stoichiometry. Heterotrophic bacteria are assumed to always be at non-limiting biomass densities. For de/nitrifying bacteria, bacterial response times to changes in substrate loading rates are considered. Nitrogen fixing blue-green algae (Cyanobacteria) are considered under phytoplankton processes.

A.3.2.2. Application. Bacterial process rates are used in mass balances for particulate and settled organic solids and related metabolic compounds.

A.3.2.3. Validation. Trial applications under various water quality conditions gave results comparable to reported water quality regimes and reported decay rates of particulate and settled solids.

A.3.3. Phytoplankton processes

A.3.3.1. Methods. Phytoplankton is modeled as a single functional group of combined species (e.g., diatoms, green algae, and blue-green algae). Gross primary productivity (GPP; g C m$^{-3}$ day$^{-1}$) is a function of: (1) phytoplankton density (g C m$^{-3}$); (2) maximum specific growth rate (d$^{-1}$); (3) light intensity penetrating the water surface and column; (4) water temperature and pH; and (5) DIC, DIN, and DIP using multiple substrate Michaelis–Menten kinetics. Net primary productivity (NPP; g C m$^{-3}$ day$^{-1}$) is a function of GPP and phytoplankton respiration. Consumption and excretion rates of additional compounds are based on metabolic stoichiometry, for which DN fixation by blue-green algae (Cyanobacteria) can be considered. Grazing by zooplankton is not considered and can be accounted for in the phytoplankton death rate term. (References used include: Steele, 1962; Eppliey et al., 1969; Toetz et al., 1973; Almazan and Boyd, 1978a; Fritz et al., 1979; El Samra and Olah, 1979; McCarthy, 1981; Stumm and Morgan, 1981; Field and Effler, 1982; Svirezhev et al., 1984; James, 1984c; Fritz, 1985; Straskraba and Gnauck, 1985; Lin et al., 1989; Piedrahita, 1990; Piedrahita et al., 1993; Giovannini and Piedrahita, 1994; Nath, 1996).

A.3.3.2. Application. Phytoplankton process rates are used in mass balances for phytoplankton, related metabolic compounds, and organic solids (dead phytoplankton contribute directly to particulate organic solids).
A.3.3.3. Validation. Trial applications under various climate and water quality conditions gave results comparable to phytoplankton density and NPP regimes reported in the literature.

A.4. Fish biologist: methods, application, and validation

A.4.1. Fish water quality criteria and performance scalars

A.4.1.1. Methods. Fish water quality criteria consist of species specific, minimum and maximum values for tolerance and optimum ranges of water quality variables (Fry, 1947, 1971; Warren and Davis, 1967; Warren, 1971; Brett, 1979; Brett and Groves, 1979; Svirezhev et al., 1984; Cuenco et al., 1985b; Ernst, 2000b). Fish performance scalars vary from 0 to 100% as water quality variables vary from tolerance extremes to the optimum region. Scalars are calculated for each variable, using linear, exponential, and/or polynomial functions, and combined based on their product (interactive variables) and/or minimum (non-interactive variables). Fish performance scalars are applied to broodfish maturation rate, egg development rate, and fish feeding and growth rates. Benthic culture species (e.g. shrimp) in stratified rearing units are subject to benthic water quality, otherwise water column mean values are used.

A.4.1.2. Application. Fish performance scaling is used to account for the impact of water quality on fish development and growth rates.

A.4.1.3. Validation. Method validity depends on the accuracy of given water quality criteria and is limited by the simplifying assumptions used.

A.4.2. Fish mortality

A.4.2.1. Methods. Fish lot mortality is a function of time and a given daily mortality rate (% day$^{-1}$), assuming exponential decay, for which the mortality rate is calculated from the expected total mortality for the culture period. For growout fish, mortality rates can be specific to fish size-stages. Total fish lot mortality occurs when one or more water quality variables exceed their tolerance range for a period of 1 day or more.

A.4.2.2. Application. Mortality rates are used to estimate fish population numbers over the culture period based on initial fish numbers. Fish population numbers are required to determine fish biomass levels from mean fish weights.

A.4.2.3. Validation. Method validity depends on the accuracy of given mortality rates.
A.4.3. Fish maturation and spawning

A.4.3.1. Methods. Fish sexual maturation is based on accumulated temperature units (ATU, degree-days) and/or photoperiod units (APU, hour-days) required to achieve spawning condition, for fish above a minimum size and within required temperature and day length ranges (Blaxter, 1969; Hoar, 1969; Piper et al., 1986). A specified female-male sex ratio is used for spawning and egg production per female is a function of fish size (length or weight). Depending on fish species, fish can spawn once per year, repeat spawn, or die after spawning.

A.4.3.2. Application. Fish maturation rates are used to schedule broodfish maturation periods and spawning events. Broodfish egg production is used to generate egg population numbers from broodfish population numbers.

A.4.3.3. Validation. Method validity depends on the accuracy of given maturation and fecundity parameters.

A.4.4. Egg incubation

A.4.4.1. Methods. Egg and larvae development is based on accumulated temperature units (ATU, degree-days) required to achieve major development stages: eyed egg, hatched larvae, and first-feeding fry (Blaxter, 1969; Piper et al., 1986).

A.4.4.2. Application. Egg development rates are used to schedule egg incubation periods and handling events.

A.4.4.3. Validation. Method validity depends on the accuracy of given temperature unit requirements.

A.4.5. Fish growth

A.4.5.1. Methods. Maximum fish growth rates at maximum feeding rates (at or near satiation) are a function of fish size, water temperature, water quality (optional), and feed quality (optional) (Ernst, 2000a). Maximum growth rates are adjusted to target growth rates by control of feeding rates. Alternative growth models include the: (1) length growth rate function (Haskell, 1959; Ricker, 1975, 1979; Piper et al., 1986; Soderberg, 1990, 1992); (2) double-logarithmic specific growth rate function (Parker and Larkin, 1959; Iwama and Tautz, 1981; Jobling, 1983; Allen et al., 1984; Jensen, 1985; Weatherley and Gill, 1987; Hepher, 1988); (3) von Bertalanffy growth function (Ricker, 1975; Hopkins et al., 1988; Hopkins, 1992; Prein et al., 1993; Froese and Pauly, 1996); and (4) anabolic-catabolic bioenergetic growth function (Ursin, 1967, 1979; Brett and Groves, 1979; Liu and Chang, 1992; Nath 1996).

A.4.5.2. Application. Fish growth rates are used to generate fish weight schedules. Weight schedules are combined with population schedules to generate fish biomass schedules.
A.4.5.3. Validation. The listed methods have been calibrated and validated for various fish species and calibration procedures have been described (see references). Reported and newly derived parameters used in trial applications with various fish species gave results comparable to reported fish weight schedules.

A.4.6. Natural fish productivity

A.4.6.1. Methods. Natural (endogenous) fish productivity (NFP; kg fish ha\(^{-1}\) day\(^{-1}\)) is determined by empirically based estimates of NFP as a function of primary productivity and/or fish biomass density (kg fish ha\(^{-1}\)), the latter utilizing ‘critical standing crop’ and ‘carrying capacity’ density parameters (McConnell et al., 1977; Almazan and Boyd, 1978b; Colman and Edwards, 1987; Hepher, 1988; Schroeder et al., 1990; Knud-Hansen et al., 1991; Diana, 1997; Ernst, 2000a). The procedure accounts for trends in NFP over a fish culture period, in which endogenous food resources may be initially high or unlimiting and subsequently exhausted, as a function of increasing fish density and food consumption in association with fish growth.

A.4.6.2. Application. NFP is applied to fish feeding and growth rates and can be used alone or in conjunction with supplemental, prepared feeds. Fish consumption rates of phytoplankton and organic solids are included in their respective mass balances.

A.4.6.3. Validation. Method validity is largely dependent on the given, empirically based parameters used to relate primary productivity, fish density, and NFP. Trial applications to pond based tilapia production gave characteristic profiles of fish productivity over time that were comparable to productivity regimes reported in the literature.

A.4.7. Fish feeding (prepared feeds)

A.4.7.1. Methods. Maximum fish feeding rates (at or near satiation) are a function of fish size, water temperature, water quality (optional), and feed quality (optional). Maximum feeding rates are adjusted to actual feed application rates based on target fish growth rates. The response of food conversion efficiency to feeding rate (Brett, 1979; Corey and English, 1985), fish competition for limited food resources, and contributions from endogenous food resources can be considered. Alternative feed models include: (1) feed rate tables (feed manufacturers and aquaculture literature); (2) food conversion efficiency functions or tables used in conjunction with fish growth rates; (3) double-log specific feeding rate function (Balarin and Haller, 1982; Ernst et al., 1989); and (4) bioenergetic feeding function (Nath 1996).

A.4.7.2. Application. Fish feeding rates are used to generate feed application schedules and to compile total feed quantities. Fish feeding rates are used in fish metabolic modeling.
A.4.7.3. **Validation.** The listed methods have been calibrated and validated for various fish species and calibration procedures have been described (see listed references). Reported and newly derived parameters used in trial applications with various fish species gave results comparable to reported feed application rate schedules.

A.4.8. **Fish metabolism**

A.4.8.1. **Methods.** Fish oxygen consumption, metabolite excretion, and fecal egestion rates \((\text{g-compound kg-fish}^{-1} \text{ day}^{-1})\) are a function of fish feeding rate, digestion and conversion efficiencies, feed composition and stoichiometry of feed catabolism, fish composition (optional), water quality (optional), and baseline standard metabolism (optional) (Speece, 1973; Brett and Zala, 1975; Huisman, 1976; Brett, 1979; Brett and Groves, 1979; Hepher, 1988; Meyer-Burgdorff et al., 1989; Colt and Orwicz, 1991b; Jobling, 1994; Ernst, 2000a). For eggs, metabolic rates are a function of water temperature. Daily simulations use daily mean metabolic rates. Diurnal simulations can be used to consider daily profiles of fish metabolism based on diurnal water temperatures and fish feeding times and amounts.

A.4.8.2. **Application.** Fish oxygen consumption and metabolite/fecal excretion rates are used in their respective mass balances.

A.4.8.3. **Validation.** Method validity depends on the accuracy of given metabolic parameters (see listed references) and calculated efficiencies of food digestion and conversion. Reported and newly derived parameters and methods used in trial applications with various fish species gave results comparable to reported metabolic rates.

**References**


